USAAMRDL TECHNICAL REPORT 72-19

OIL-STARVATION TEST PROGRAM: EVALUATION OF VASCO-X2 STEEL SPIRAL BEVEL GEARS

FINAL REPORT

By

J. P. Alberti
A. J. Lemanski

April 1972

EUSTIS DIRECTORATE
U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

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THE BOEING COMPANY, VERTOL DIVISION
PHILADELPHIA, PENNSYLVANIA

U. S. ARMY MATERIEL COMMAND

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This report was prepared by the Boeing Company, Vertol Division under the terms of Contract DAAJ02-72-C-0009.

In this effort, it was shown that the current state-of-the-art transmission gear material is not capable of operation at 100-percent power for 30 minutes in a nonlubricated environment. The results indicate that there must be some amount of lubrication or cooling to prevent the gear temperature from reaching a point where the metal begins to flow and failure occurs. Further study is indicated to develop a thermal map of the transmission which would be useful in predicting the minimum amount of lubrication or cooling that is necessary.

The technical monitors for this contract were Mr. James T. Robinson and SP4 Vick M. Crawley of the Safety and Survivability Division.

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13. ABSTRACT

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Spiral bevel gears made from AISI 9310 steel and identical gears made from VASCO-X2 steel were run under load in a regenerative (four-square) test stand. The purpose of this testing was to evaluate the effect of material properties on the performance of main power gears in a non-lubricated (loss-of-oil) environment.

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Prepared by

The Boeing Company, Vertol Division
Philadelphia, Pennsylvania

for

EUSTIS DIRECTORATE
U.S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

IV

SUMMARY

This report presents the results of tests conducted to evaluate the performance of spiral bevel gears made from VASCO-X2 steel when they are operated without lubricating oil.

Spiral bevel gears made from AISI 9310 steel and identical gears made from VASCO-X2 steel were run under load in a regenerative (four-square) test stand. The purpose of this testing was to evaluate the effect of material properties on the performance of main power gears in a nonlubricated (loss-of-oil) environment.

The general conclusions of this report are summarized as follows:

1. The attempt to measure gear-blank temperature by the use of temp-plate sensors was not successful, because the sensors failed under exposure to oil and very high temperatures. The use of thermal crayons for the relative measurement of gear-blank temperature, however, was successful, in that comparative temperature determinations were made between the various tests.

2. The gear steel compositions used in this program did not show a significant difference in operating time (nonlubricated) at the full load level.

3. The increased backlash (approximately 2 to 1) resulting from the original regrind of the test specimens appeared to be insufficient to accommodate the thermal expansion experienced during the nonlubrication testing at the 100-percent and 85-percent load levels.

4. Test runs at the 75-percent load level resulted in light surface distress, indicating that the operational load has a significant effect on survival time after a lubrication failure.

5. There were insufficient test data points to establish a statistical evaluation of the test results.

FOREWORD

This program was conducted during the period August 1971 through December 1971 for the Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory, Ft. Eustis, Virginia, by the Vertol Division of Boeing, under Contract DAAJ02-72-C-0009 (DA Task 1F162205AA5201).

Technical direction was provided by Mr. J. Robinson, Project Engineer, Safety and Survivability Division.

The program was conducted at the Vertol Division of the Boeing Company under the technical direction of A. J. Lemanski, Chief of the Advanced Drive System Technology Department. Principal investigators for the program were J. P. Alberti, Project Engineer, and J. C. Leeds, Assistant Project Engineer.

Acknowledgment is made to Professors W. J. Murphy and J. Curry and their staff at Villanova University for their assistance and contributions during the experimental test program.

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INTRODUCTION

The objective of this program was to investigate the potential of improving the survivability time of the main power spiral gears in an emergency nonlubricated environment by experimentally testing bevel gears fabricated from a carburized, high-hot-hardness, tool steel.

Considerable effort has been expended by industry in recent years in the development of failsafe rolling-element bearing designs with the capability of emergency operation in a hostile (loss of oil) environment for a reasonable length of time. However, the practicality of extended survivability for a helicopter power transmission is also dependent on the final development of a failsafe power gear train and a supporting bearing system.

The results of several recently completed gear test programs by Boeing's Vertol Division have indicated that the high-hot-hardness characteristics of VASCO-X2 steel have the potential for improved performance in a high-load and/or high-temperature operating environment.

This report presents the results of a program conducted by Vertol to evaluate the performance in a nonlubricated environment of main power spiral bevel gears manufactured from the currently used gear steel, AISI 9310 (AMS6265), and from VASCO-X2 steel.

TECHNICAL APPROACH

BACKGROUND

Previous development efforts to improve power transmission gear materials have not considered high-hot-hardness characteristics and emergency operation under no-oil conditions. The need for improved gear materials has usually been based on the desire for higher load-carrying capacity without increases in gear size. This requirement has resulted in an effort to improve core strength and hardenability. In the past, gear steel development has been essentially limited to the addition of varying quantities of carbon, chromium, nickel, and molybdenum as alloying elements. However, the choice of alloying elements is dictated by the effects of the elements on the uniformity of carburizing and the compatibility of case-core heat treatment. The present standard gear material of the aerospace industry is AISI 9310 steel. This material incorporates these alloying elements to a degree and generally provides a good combination of properties. The current aerospace gear steels are heat-treated by conventional quench and tempering methods.

In the past, helicopter main power gear design was based primarily on bending fatigue strength, usually resulting in the selection of coarse-pitch tooth designs. This approach has often limited the surface durability in favor of bending strength and produced early surface failures (scuffing, pitting, etc.). Scoring (scuffing) is a phenomenon which occurs when the film of lubricating oil breaks down and permits metal-to-metal contact of the gear tooth surfaces. This metal-to-metal contact results in the development of high frictional heat which, in turn, tempers the gear tooth surfaces. Continued operation under these conditions will ultimately produce metal flow, which alters the tooth profiles and destroys the load-carrying capacity of the gear set.

Advanced gear materials now in the process of development indicate the capability to resist plastic flow at elevated temperatures. Past experience with helicopter transmission operation during emergency conditions (loss of lubrication) indicates that the resulting high-temperature environment requires a gear material with the capability of resisting excessive erosion and softening of the carburized case, and still maintain sufficient hardness. The candidate materials

under development that display this potential are secondary hardening steels, similar to those used in tool fabrication. These materials develop their maximum hardness by tempering between 950°F and 1100°F. Thermal exposure of these materials to temperatures below the tempering range will not significantly alter room temperature hardness, as compared to conventional carburizing steels that will display case softening at temperatures as low as 350°F.

STATEMENT OF PROBLEM

The main gearboxes of current helicopter power transfer systems are the heart of the propulsion system, charged with tremendous responsibility for safe flight of the entire aircraft. There are few other types of vehicles which place such stringent demands on power gears and bearings for reliability and performance. Combat operation of helicopters in Southeast Asia has shown that the helicopter oil-cooling system is susceptible to combat damage due to the remote location of coolers and blowers with their extensive plumbing systems.

This service experience (corroborated by tests) indicates the dependence of the helicopter transmission system on a continuous flow of lubricating oil to the main power gears and bearings. On the occasions when the oil supply has been interrupted, the transmission survival times are of extremely short duration, particularly in the area of high input speed.

Interruption of this oil flow from any cause would normally dictate an immediate power-off descent and landing. Under certain circumstances, such as over open water, over enemy terrain, or in the dark, this would be a hazardous operation. It is therefore obvious that a need exists for prolonging the safe operation of the drive system for approximately 30 minutes after the loss of oil.

Main power gearing in current helicopter transmissions is limited in load-carrying capacity by the fact that current gear materials are subject to early surface failures in the form of scuffing, pitting, or spalling. The bending strength and flexural resistance of these materials have not typically imposed significant limitations on performance.

The primary concern of the transmission gear design engineer is to provide adequate tooth strength in order to preclude the possibility of catastrophic failure; therefore, gear materials have been selected on the basis of beam strength requirements. The current family of aerospace carburizing gear steels has very limited hot-hardness capability. Experience with these steels has not demonstrated a significant effect in resisting the scuffing or pitting hazard. The implication is that these steels will not provide adequate survival time under conditions of total oil loss, whereas a hot-hardness steel could provide for an adequate failsafe operating time period.

The contractor has conducted several programs under Government and company funding to evaluate candidate advanced gear materials. One material is identified by nomenclature as VASCO-X2 steel. Several formulations of this high-hot-hardness tool steel have been investigated. Some formulations differed in chemical composition; the percentages of both carbon and tungsten were varied. The test data from these programs revealed that certain formulations of VASCO-X2 steel permitted a substantial increase in tooth loading without resulting in a surface or bending tooth failure.

TEST METHOD

TEST SPECIMEN DESIGN

Spiral bevel gears from a previous Government-sponsored test program (Contract DAAJ01-70-C-0453(1G), AVSCOM) were used as the test specimens.

Eight each spiral bevel pinions and gears of AISI 9310 AMS6265 steel, part numbers SK23409-1 and SK23410-1, were reground to remove the tooth surface finish resulting from the previous program for use as the baseline test gears. Eight each spiral bevel pinions and gears of VASCO-X2 consumable-electrode vacuum-melt (CVM) steel, part numbers SK23411-1 and SK23412-1, were reground to remove the tooth surface finish from the previous program and were used as the test gears for comparison with the baseline gears. All the test specimens were designed to the following general specifications:

Diametral Pitch	5.833 (nondimensional)
Pitch Diameter	Pinion 6.00 inches, gear 7.372 inches
Face Width	1.426 inches
Number of Teeth	Pinion 35, gear 43
Pressure Angle	22 degrees 36 minutes
Spiral Angle	26 degrees

The detail specifications for the test gears are shown in the engineering drawings, figures 1 through 4.

MATERIAL

The baseline spiral bevel test pinions (SK23409-1) and test gears (SK23410-1) were made of AISI 9310 (AMS6265) consumable-electrode vacuum-melt steel. This material is currently used for most helicopter main power gears. The remaining test spiral bevel pinions (SK23411-1) and test gears (SK23412-1) were of VASCO-X2 (0.15 carbon) consumable-electrode vacuum-melt steel. This steel had shown promise of increased

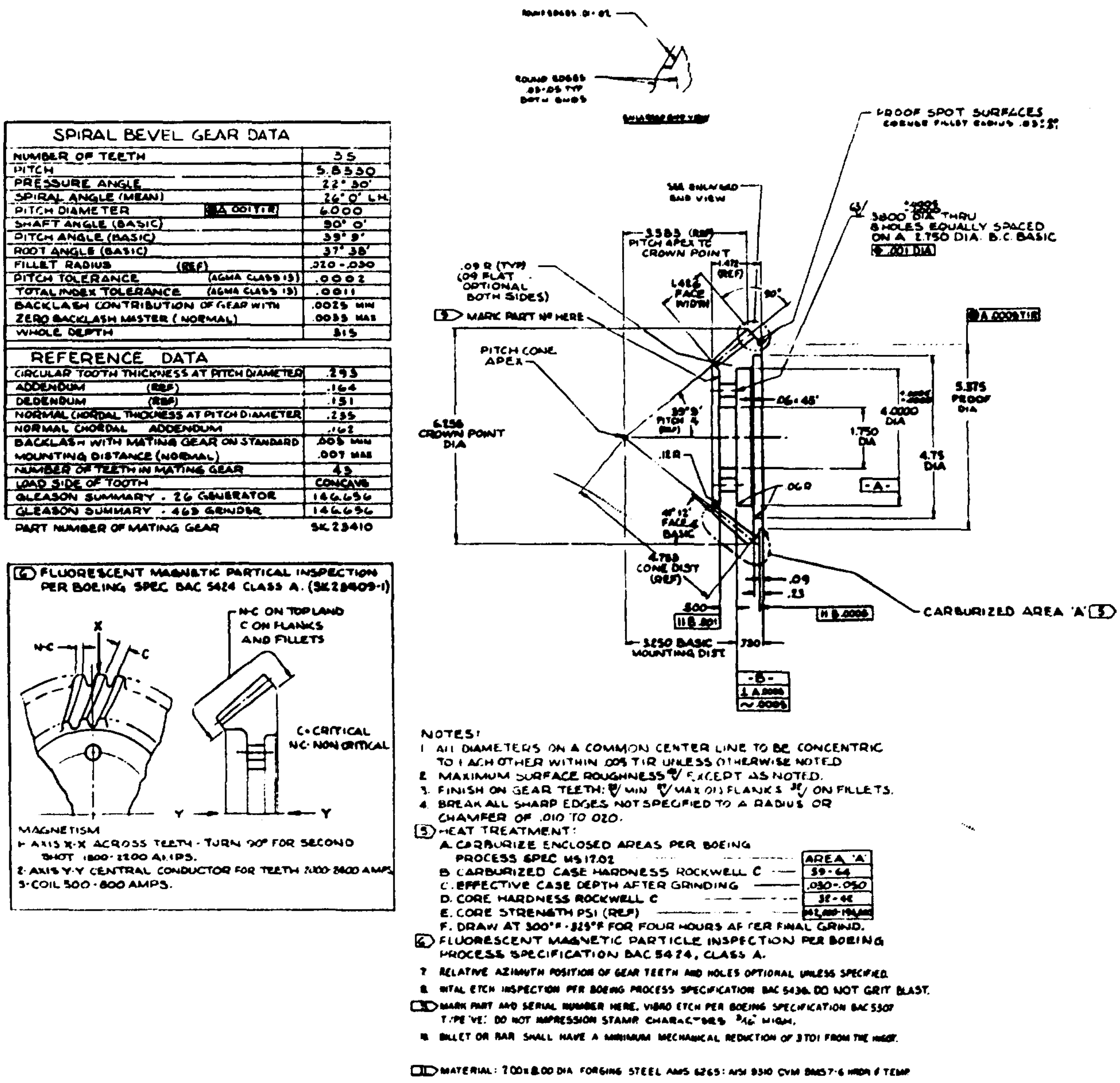
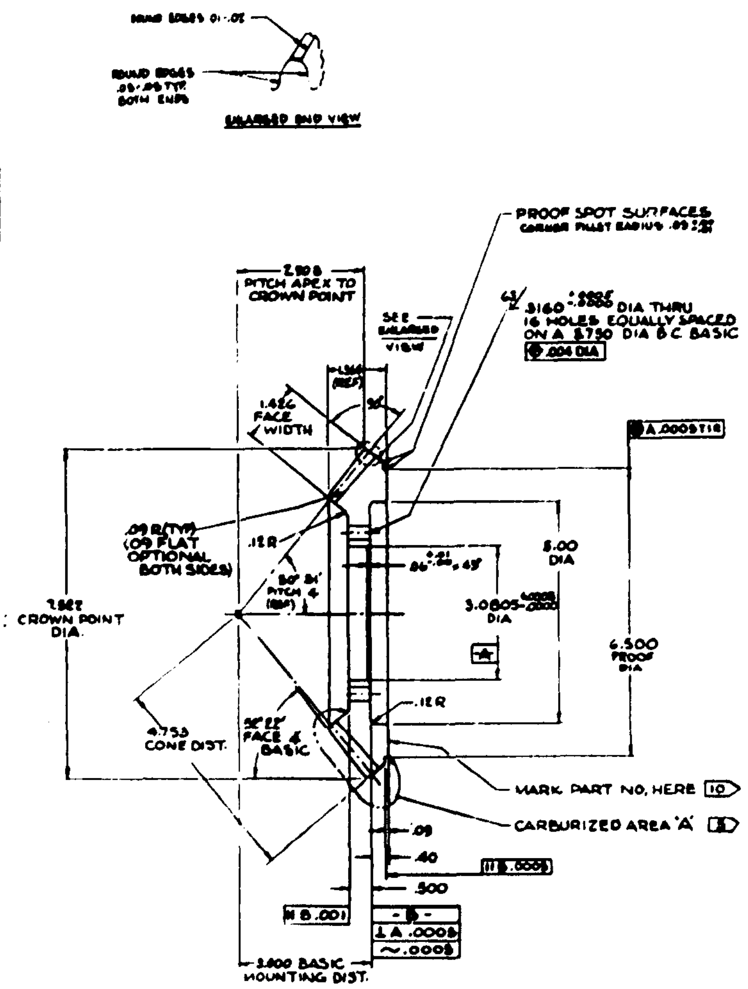


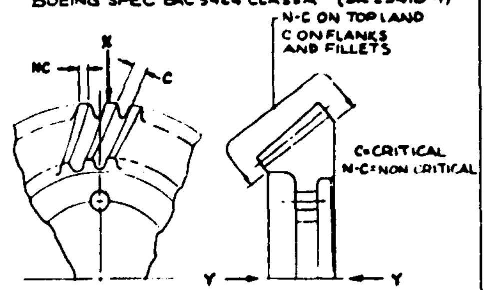
Figure 1. Baseline Test Gears (AISI 9310 Steel)--
Spiral Bevel Pinion, Part No. SK23409-1.



SPIRAL BEVEL GEAR DATA	
NUMBER OF TEETH	43
PITCH	5.8330
PRESSURE ANGLE	22° 30' 0"
SPIRAL ANGLE (MEAN)	26° 0' RH
PITCH DIAMETER A .001 TIR	7.372
SHAFT ANGLE (BASIC)	90° 0'
PITCH ANGLE (BASIC)	50° 51'
ROOT ANGLE (BASIC)	48° 48'
FILLET RADIUS (REF)	.040 -.060
PITCH TOLERANCE (AGMA CLASS 13)	.0002
TOTAL INDEX TOLERANCE (AGMA CLASS 13)	.0011
BACKLASH CONTRIBUTION OF GEAR WITH ZERO BACKLASH MASTER (NORMAL)	.0025 MIN. .0035 MAX.
WHOLE DEPTH	.318

REFERENCE DATA	
CIRCULAR TOOTH THICKNESS AT PITCH DIAMETER	.236
ADDENDUM (REF)	.119
DEDENDUM (REF)	.196
NORMAL CHORDAL THICKNESS AT PITCH DIAMETER	.193
NORMAL CHORDAL ADDENDUM	.118
BACKLASH WITH MATING GEAR ON STANDARD MOUNTING DISTANCE (NORMAL)	.005 MIN .007 MAX
NUMBER OF TEETH IN MATING GEAR	35
LOAD SIDE OF TOOTH	CONVEX
GLEASON SUMMARY - 26 GENERATOR	146.656
GLEASON SUMMARY - 463 GRINDER	146.656
PART NUMBER OF MATING GEAR	SK 23409

6 FLUORESCENT MAGNETIC PARTICLE INSPECTION PER BOEING SPEC BAC 5424 CLASS A (SK 23410-1)



MAGNETISM
1- AXIS X-X ACROSS TEETH TURN 90° FOR SECOND SHOT 1800 2200 AMPS
2- AXIS Y-Y CENTRAL CONDUCTOR FOR TEETH 2000-2400 AMPS
3- COIL 500-800 AMPS

NOTES:

1. ALL DIAMETERS ON A COMMON CENTER LINE TO BE CONCENTRIC TO EACH OTHER WITHIN .005 TIR UNLESS OTHERWISE NOTED
2. MAXIMUM SURFACE ROUGHNESS 125/ EXCEPT AS NOTED.
3. FINISH ON GEAR TEETH 23/MIN 27/ MAX ON FLANKS 32/ ON FILLETS.
4. BREAK ALL SHARP EDGES NOT SPECIFIED TO A RADIUS OR CHAMFER OF .010 TO .020
5. HEAT TREATMENT:
   - A. CARBURIZE ENCLOSED AREAS PER BOEING PROCESS SPEC MB1202 — AREA 'A'
   - B. CARBURIZED CASE HARDNESS ROCKWELL C — 59-64
   - C. EFFECTIVE CASE DEPTH AFTER GRINDING — .030-.050
   - D. CORE HARDNESS ROCKWELL C — 32-42
   - E. CORE STRENGTH PSI (REF) — 142,000-194,000
   - F. DRAW AT 300°F-325°F FOR FOUR HOURS AFTER FINAL GRIND
6. FLUORESCENT MAGNETIC PARTICLE INSPECTION PER BOEING PROCESS SPECIFICATION BAC 5424, CLASS A.
7. MATERIAL: 2.00 + 8.00 DIA. FORGING STEEL AMS 6266; AISI 9310 CVM BMS 7-6 HRD & TEMP
8. RELATIVE AZIMUTH POSITION OF GEAR TEETH AND HOLES OPTIONAL UNLESS SPECIFIED
9. NITAL ETCH INSPECTION PER BOEING PROCESS SPECIFICATION BAC 5436. DO NOT GRIT BLAST
10. MARK PART AND SERIAL NUMBER HERE VIBRO ETCH PER BOEING SPECIFICATION BAC 5307 TYPE 'VE' DO NOT IMPRESSION STAMP. CHARACTERS 3/16 HIGH.
11. BILLET OR BAR SHALL HAVE A MINIMUM MECHANICAL REDUCTION OF 3 TO 1 FROM THE INGOT.

Figure 2. Baseline Test Gears (AISI 9310 Steel)--Spiral Bevel Gear, Part No. SK23410-1.

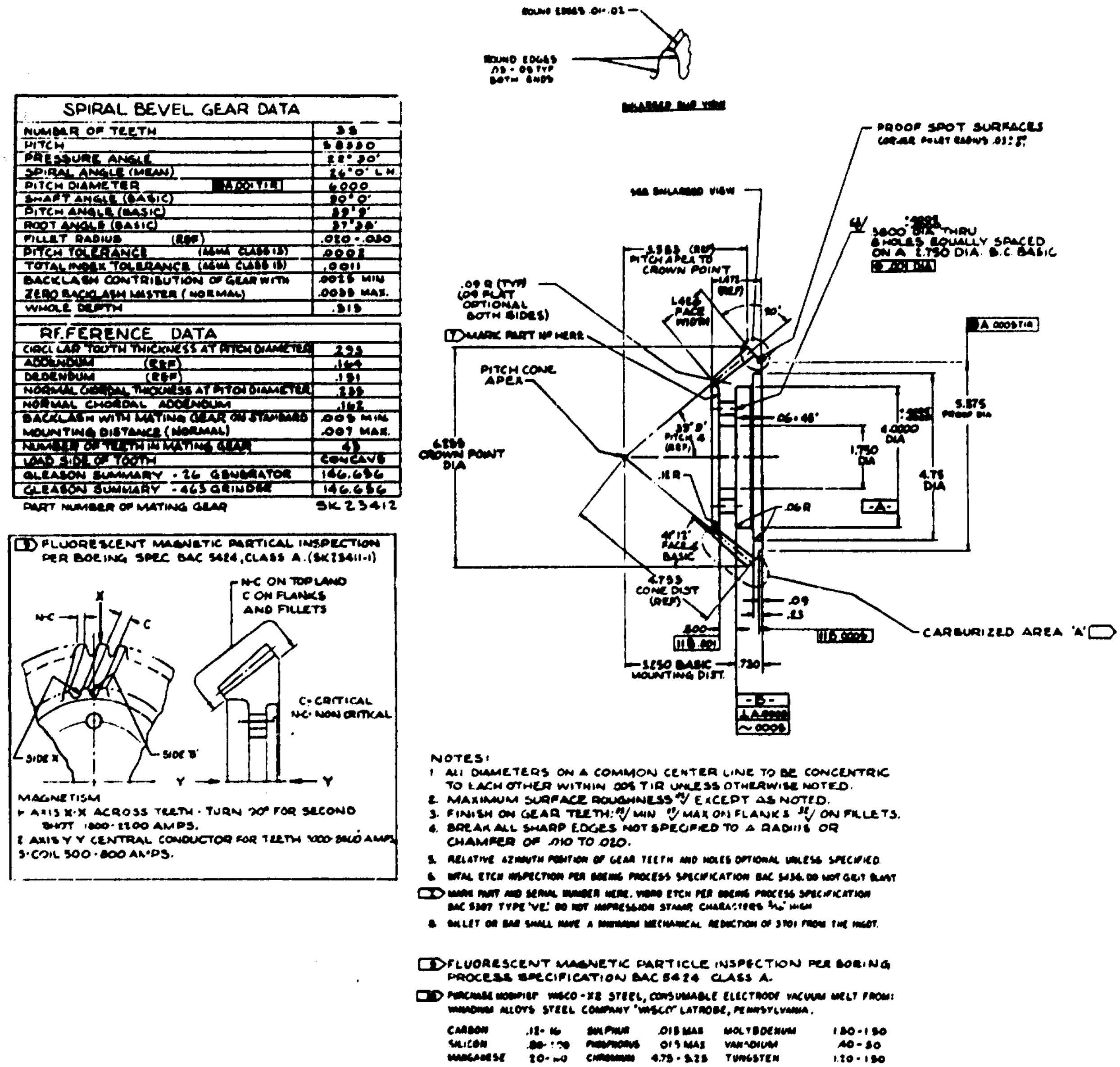


Figure 3. VASCO-X2 Test Gears--Spiral Bevel Pinion, Part No. SK23411-1.

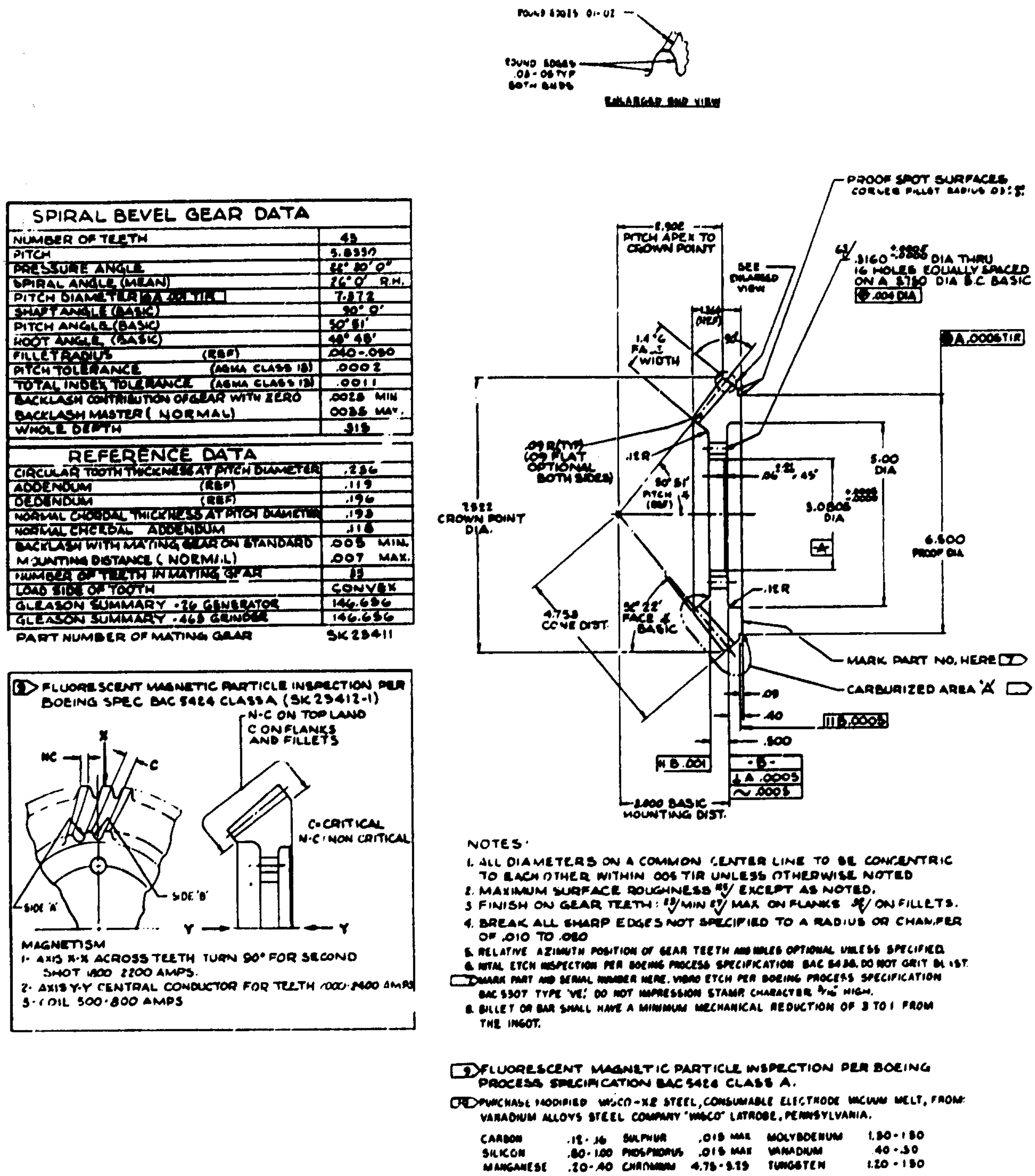


Figure 4. VASCO-X2 Test Gears--Spiral Bevel Gear, Part No. SK23412-1.

potential for surface load capacity in previous test programs, and it represented the major test variable in this test program.

FABRICATION

The test gears were manufactured earlier by Boeing-Vertol for AVSCOM under Contract DAAJ01-70-C-0453(1G). A representative sequence of manufacturing operations for the fabrication of typical aircraft spiral bevel gears is shown in Figure 5.

Eight gear sets of each type of steel were reground to remove the tooth surfaces resulting from the previous test program. The physical dimensions resulting from the regrinding process are shown in Table I. Figures 6 and 7 show the as-received condition of the gears prior to testing.

METALLURGICAL EVALUATION

Destructive metallurgical examinations were not conducted prior to implementing the test program. Table II presents the material evaluation conducted on the previously completed contract, which is representative of the test gears used for this program.

TEST APPARATUS

All gear test specimens for this program were evaluated on the Boeing-Vertol gear research test stand located at Villanova University. This test apparatus was specifically designed for research and development programs for spur, helical, and bevel gears. The design incorporates provisions for center distance option, variable speed, and control of oil temperature and oil flow. The system is a regenerative (four-square) design using one gearbox as the slave unit and one gearbox as the test unit. Gear mountings were designed to be rigid and stable under all loading conditions with through-bored housings for maximum accuracy. All gear shafting is supported on ball and roller bearings lubricated by individual oil jets.

For this test, oil slingers were fabricated and installed on the inside of the gear case on the test spiral bevel pinion and gear to prevent oil mist from the bearing lubrication from influencing the nonlubricated performance of the test gears. A remote-controlled solenoid valve was installed to close the

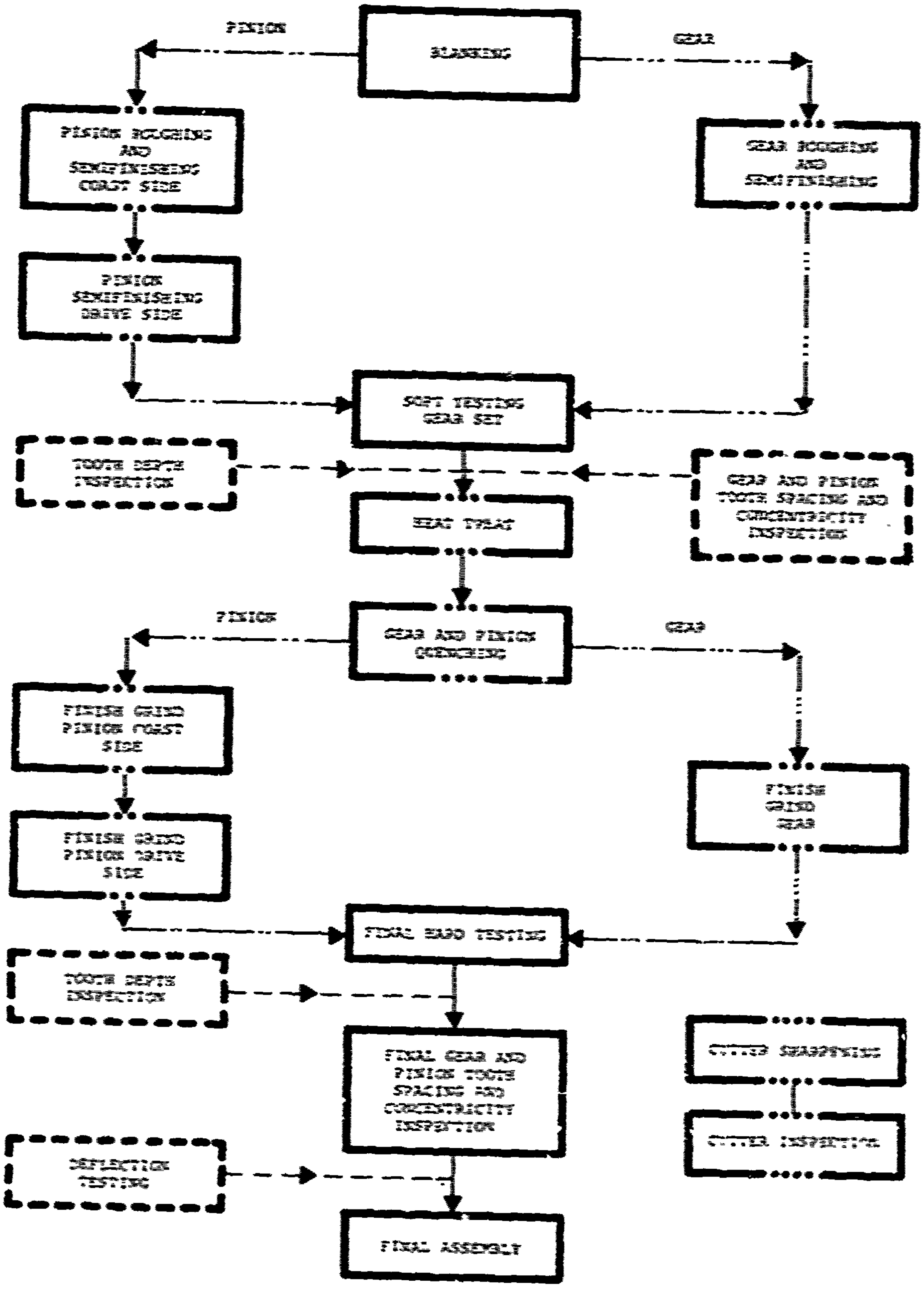


Figure 5. Fabrication Sequence for Aircraft Spiral Bevel Gears.

TABLE I. DIMENSIONAL CHARACTERISTICS OF REGROUND SPIRAL BEVEL GEARS

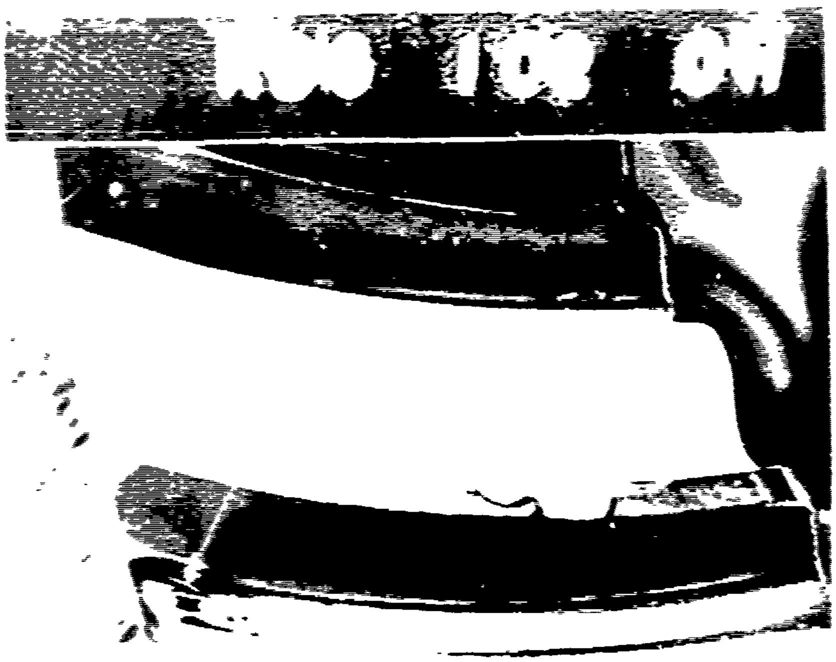
Set	Part Number	Serial Number	Removal Per Side (inch)	Tooth Finish (rms)	Assembled Backlash (inch)	Mounting Distance Tolerance (inch)
AISI 9310 (AMS6265) Steel						
1	SK23409-1	A102	0.003	23-24	0.014	0.0
	SK23410-1	A102		23-24		0.0
2	SK23409-1	A103	0.003	27-28	0.014	0.0
	SK23410-1	A103		23-24		0.0
3	SK23409-1	A104	0.0065	23-25	0.0175	0.0
	SK23410-1	A104		22-23		0.0
4	SK23409-1	A105	0.006	24-25	0.012	0.0
	SK23410-1	A105		23-24		0.0
5	SK23409-1	A106	0.002	23-25	0.013	0.0
	SK23410-1	A106		22-23		0.0
6	SK23409-1	A107	0.005	24-25	0.016	0.0
	SK23410-1	A107		23-24		0.0
7	SK23409-1	A108	0.003	24-25	0.014	0.0
	SK23410-1	A108		24		0.0
8	SK23409-1	A109	0.003	24-25	0.014	0.0
	SK23410-1	A109		23-24		-0.010
VASCO-X2 Steel						
1	SK23411-1	A101	0.004	25-26	0.014	0.0
	SK23412-1	A102	0.004	25-26		0.0
2	SK23411-1	A103	0.002	24-25	0.011	0.0
	SK23412-1	A104	0.003	24-25		0.0
3	SK23411-1	A104	0.005	24-25	0.015	0.0
	SK23412-1	A106	0.003	25-26		0.0
4	SK23411-1	A106	0.004	24-25	0.014	0.0
	SK23412-1	A107	0.003	24-25		0.0
5	SK23411-1	A109	0.004	24-25	0.014	0.0
	SK23412-1	A109	0.003	24		0.0
6	SK23411-1	A110	0.003	24-25	0.014	0.0
	SK23412-1	A110	0.003	24		0.0
7	SK23411-1	A111	0.005	25-26	0.015	0.0
	SK23412-1	A112	0.003	24-25		0.0
8	SK23411-1	A112	0.004	25-26	0.014	0.0
	SK23412-1	A113	0.004	24-25		0.0

BASELINE GEAR SET 1

Pinion Number A102

BASELINE GEAR SET 2

Pinion Number A103



Gear Number A102

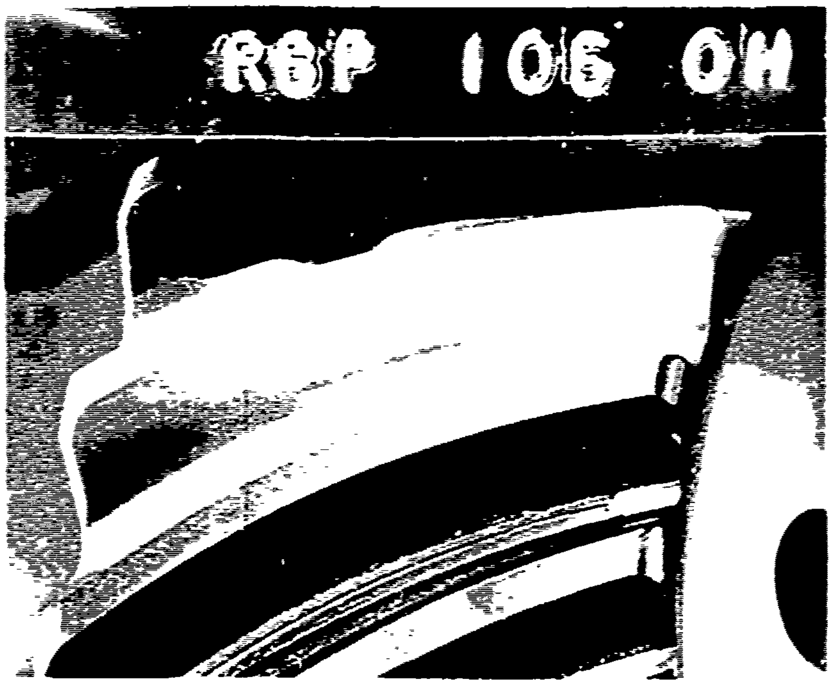
Gear Number A103

Figure 6. As-Received Condition of Baseline Test Gears (Sheet 1 of 2).

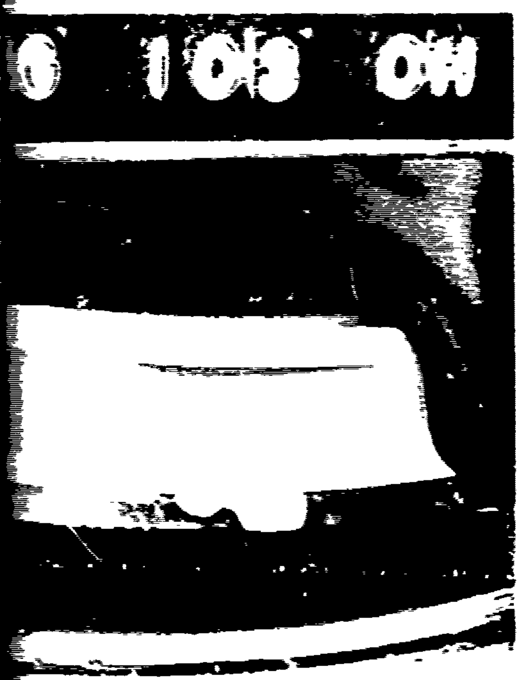
LINE GEAR SET 2

BASELINE GEAR SET 3

ion Number A103



Pinion Number A105

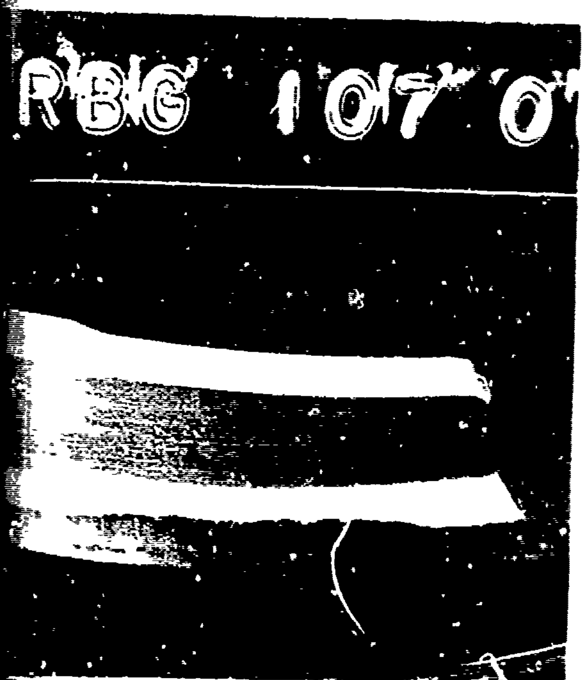


r Number A103

Gear Number A105

BASELINE GEAR SET 5

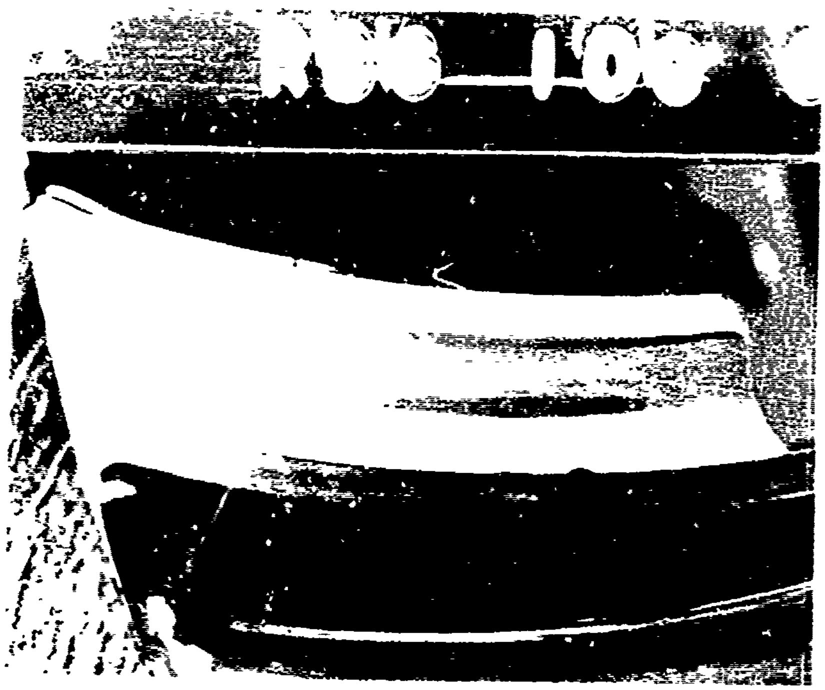
Pinion Number A107



Gear Number A107

BASELINE GEAR SET 6

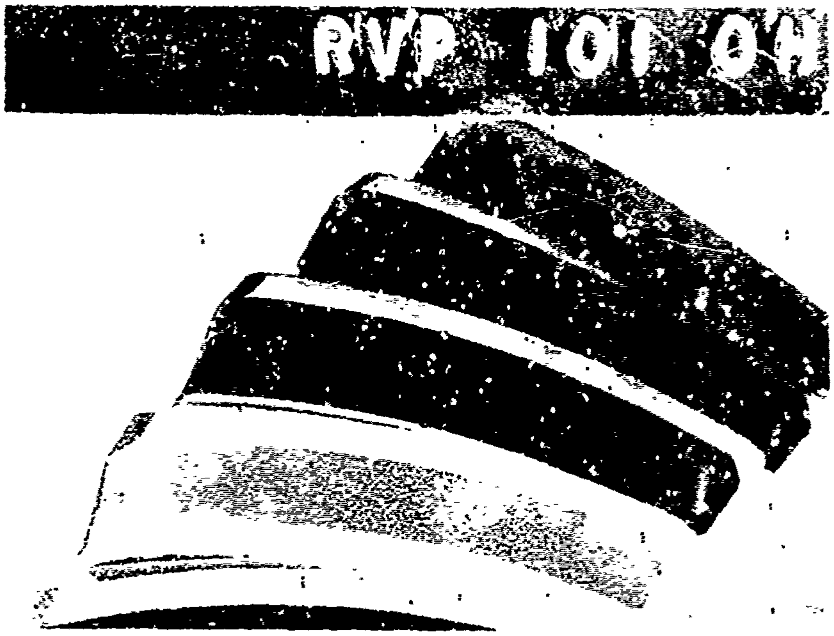
Pinion Number A108



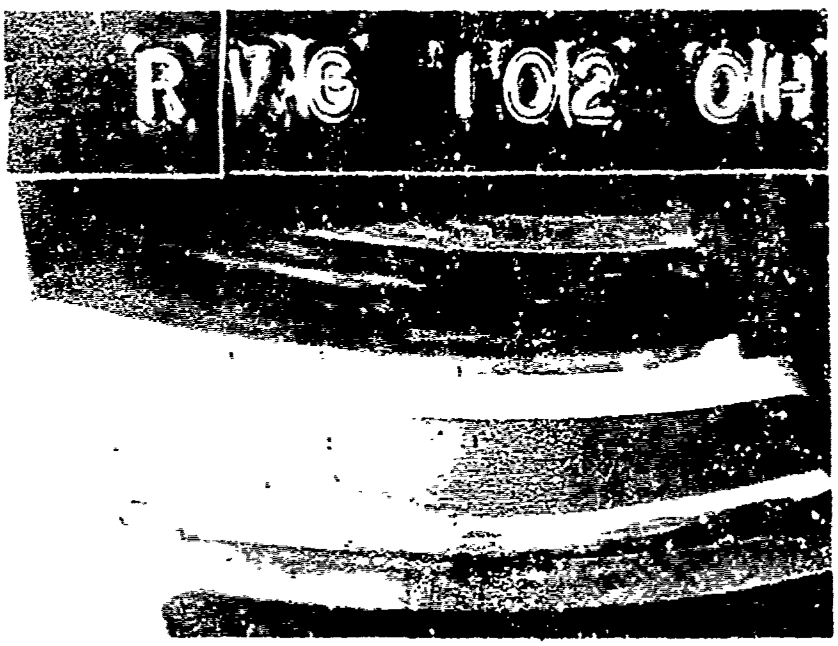
Gear Number A108

B

VASCO-X2 GEAR SET 1

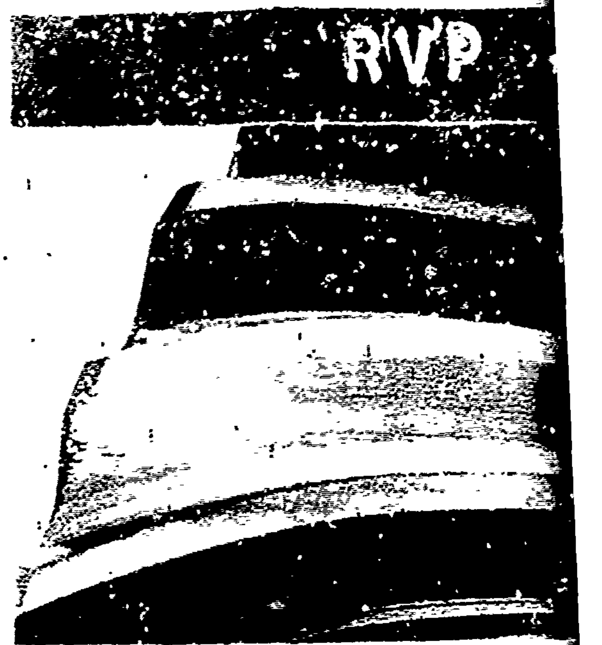


Pinion Number A101



Gear Number A102

VASCO-X2 GEAR SET



Pinion Number A104

Gear Number A106

Figure 7. As-Received Condition of VASCO-X2 Test Gears (Sheet 1 of 2).

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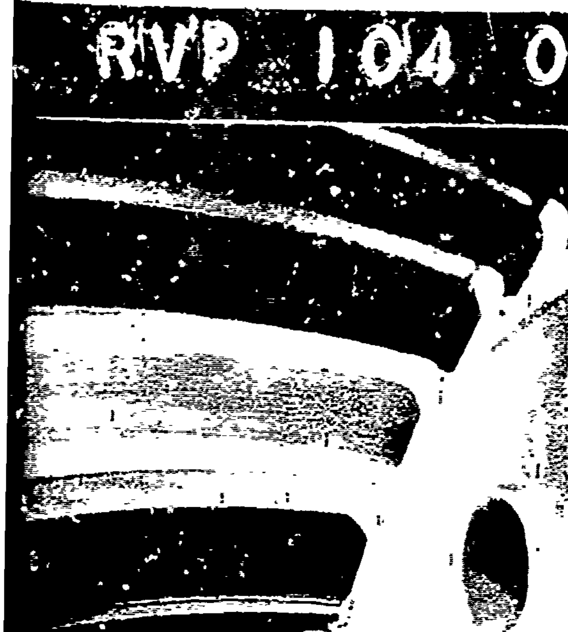
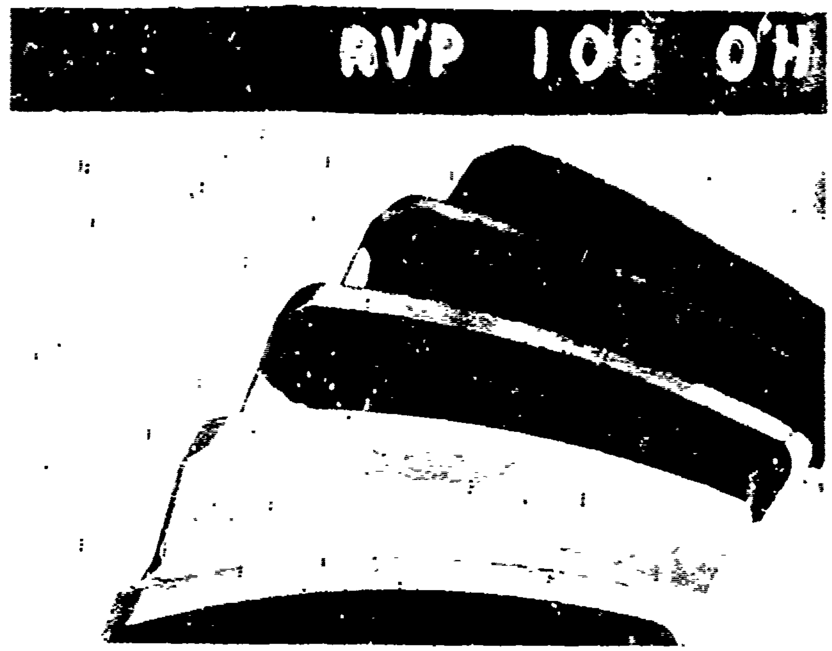
SCO-X2 GEAR SET 2

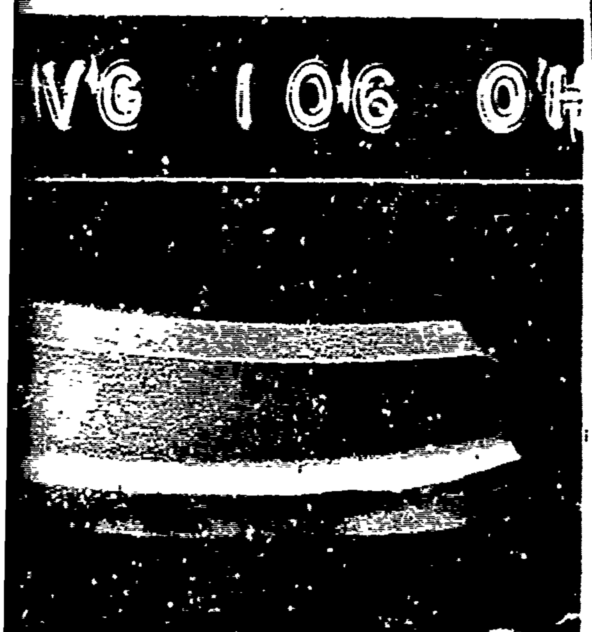
VASCO-X2 GEAR SET 3



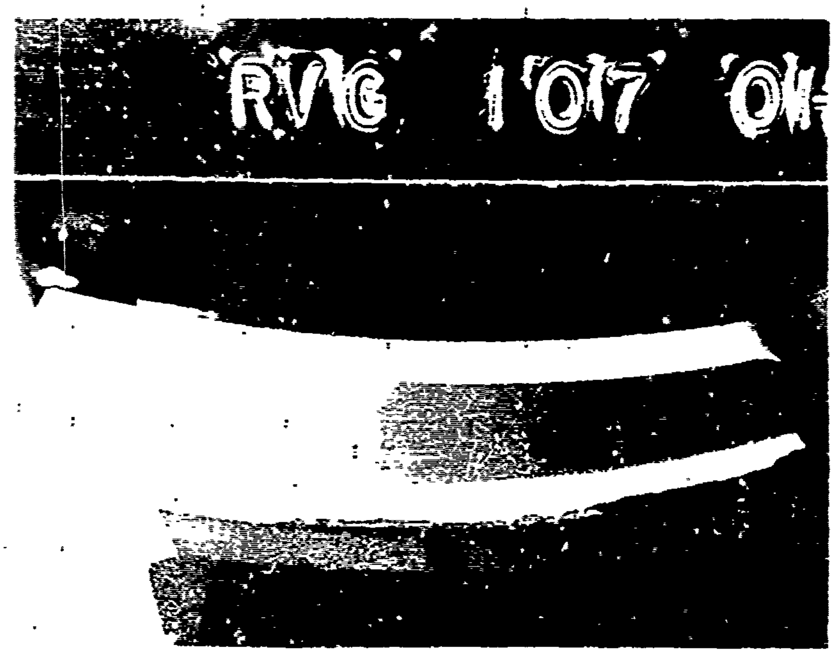
Pinion Number A104



Pinion Number A106



Gear Number A106

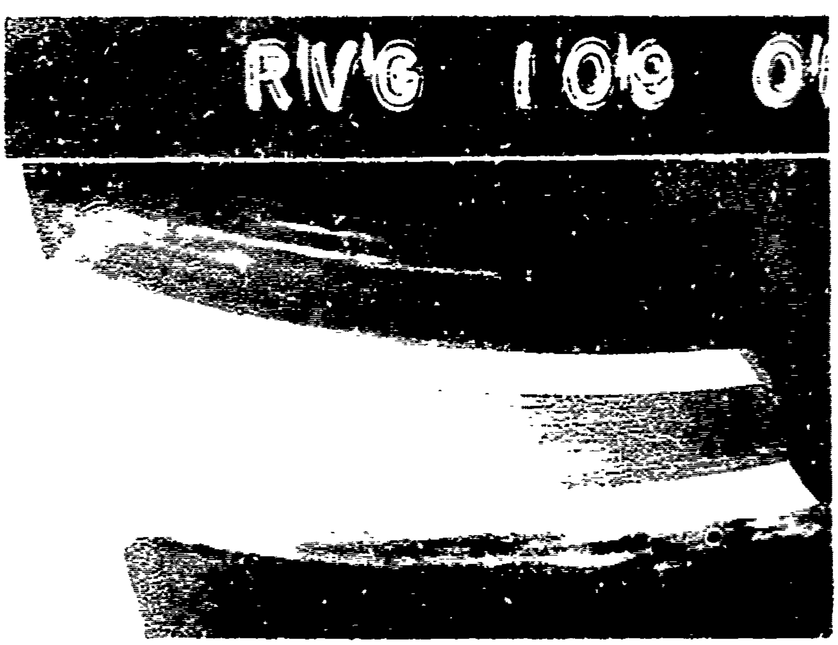


Gear Number A107

6

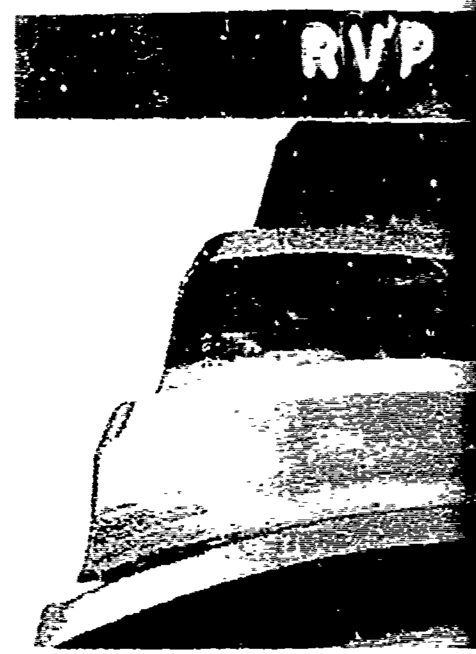
VASCO-X2 GEAR SET 4

Pinion Number A109



Gear Number A109

VASCO-X2 GEAR



Pinion Number

Gear Number

Figure 7 - Continued (Sheet 2 of 2).

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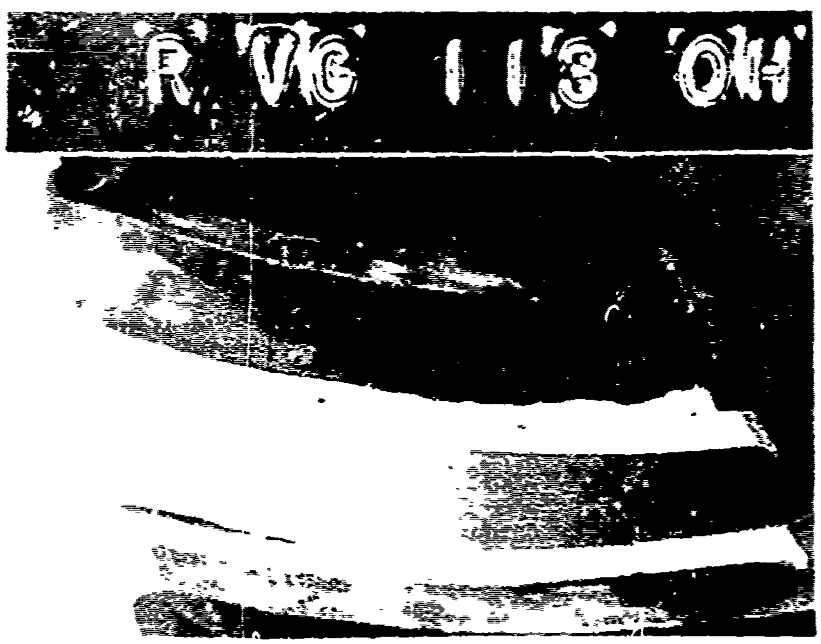
2 GEAR SET 5

Number A110

Number A110

VASCO-X2 GEAR SET 6

Pinion Number A112



Gear Number A113

B

TABLE II. CHEMICAL COMPOSITION OF TEST GEARS				
	Percent by Weight			
	AISI 9310 (AMS6265)		VASCO-X2 CVM	
Element	Specified	Actual	Specified	Actual
Carbon	0.07 to 0.13	0.11	0.12 to 0.16	0.17
Manganese	0.40 to 0.70	0.75	0.20 to 0.40	0.29
Silicon	0.20 to 0.35	0.37	0.80 to 1.00	1.00
Chromium	1.00 to 1.40	1.33	4.75 to 5.25	5.10
Molybdenum	0.08 to 0.18	0.09	1.30 to 1.50	1.50
Vanadium	-	-	0.40 to 0.50	0.52
Tungsten	-	-	1.20 to 1.50	1.38
Nickel	3.00 to 3.50	3.25	-	-
Case hardness	-	61 to 62	-	62 to 63
Core hardness	-	44	-	36
Grain size	-	-	-	8

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test gear mesh oil jet for the nonlubricated portion of the test. Figure 8 shows the configuration used for this program.

TESTING TECHNIQUE

The primary test variables were shaft torque and oil inlet temperature. Gear tooth load was a function of shaft torque, which was applied through a lever system at the beginning of each test run. Torque levels were observed on a Strainsert SR2 instrument at the beginning and end of each test run. Deviation from the initial target torque was controlled within ± 5 percent at test startup.

The torquemeter was calibrated before and after the test program on a Riehle deadweight torsion test machine (Figure 9). Recalibration curves agreed with the initial curves within 2 percent. Test time (cycles) was determined by a log record of running time and an elapsed-time meter at the test stand console. Power was supplied by a 100-hp electric motor driving the input shaft through a toothed-belt arrangement, maintaining the input pinion speed at 3,410 rpm.

Inlet oil temperature for the test gearbox was controlled at 190 ± 5°F, with an oil pressure of 55 ± 5 psi. The oil used for lubrication of the test gears was MIL-7808-G. Test runs were begun after the outlet oil temperature stabilized.

Before the test runs were begun, deflection tests were conducted by mounting the test gears in the test box, applying specified loads, and rotating the gear set through mesh by hand, to evaluate the contact pattern (load distribution).

The test procedure used for all gears in this program was the same. Each gear set (spiral bevel pinion and gear) was installed in the test gearbox, with the specified backlash at the specified mounting distance. The lubricating oil was heated to 190 ± 5°F and then circulated by the pumps. Torque was applied after stabilization of the oil outlet temperature; the test run began at this point. The test schedule given in Table III was performed on both the AISI 9310 steel and the VASCO-X2 steel spiral bevel gears as follows:

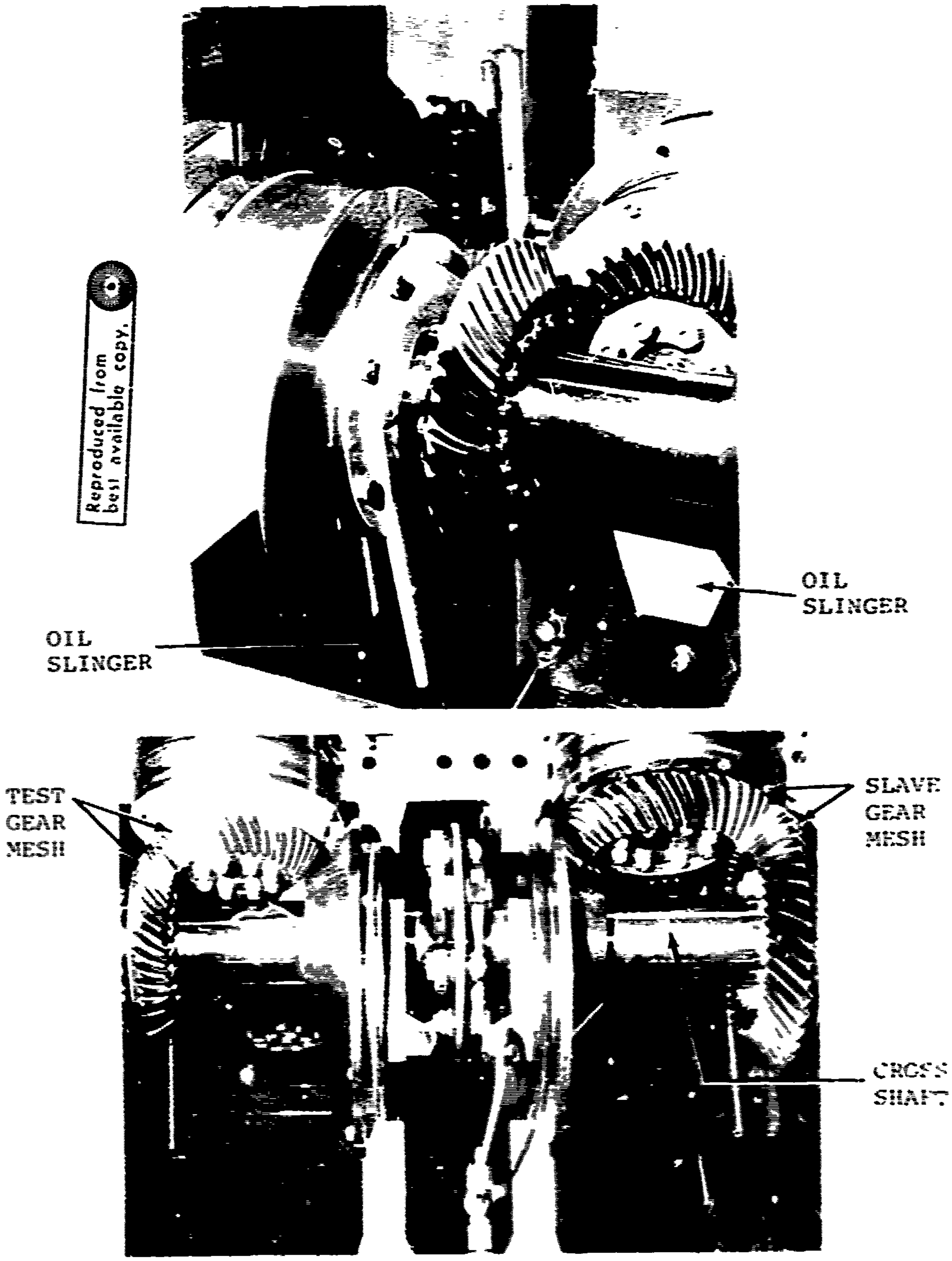


Figure 8. Boeing-Vertol Gear Research Test Stand.

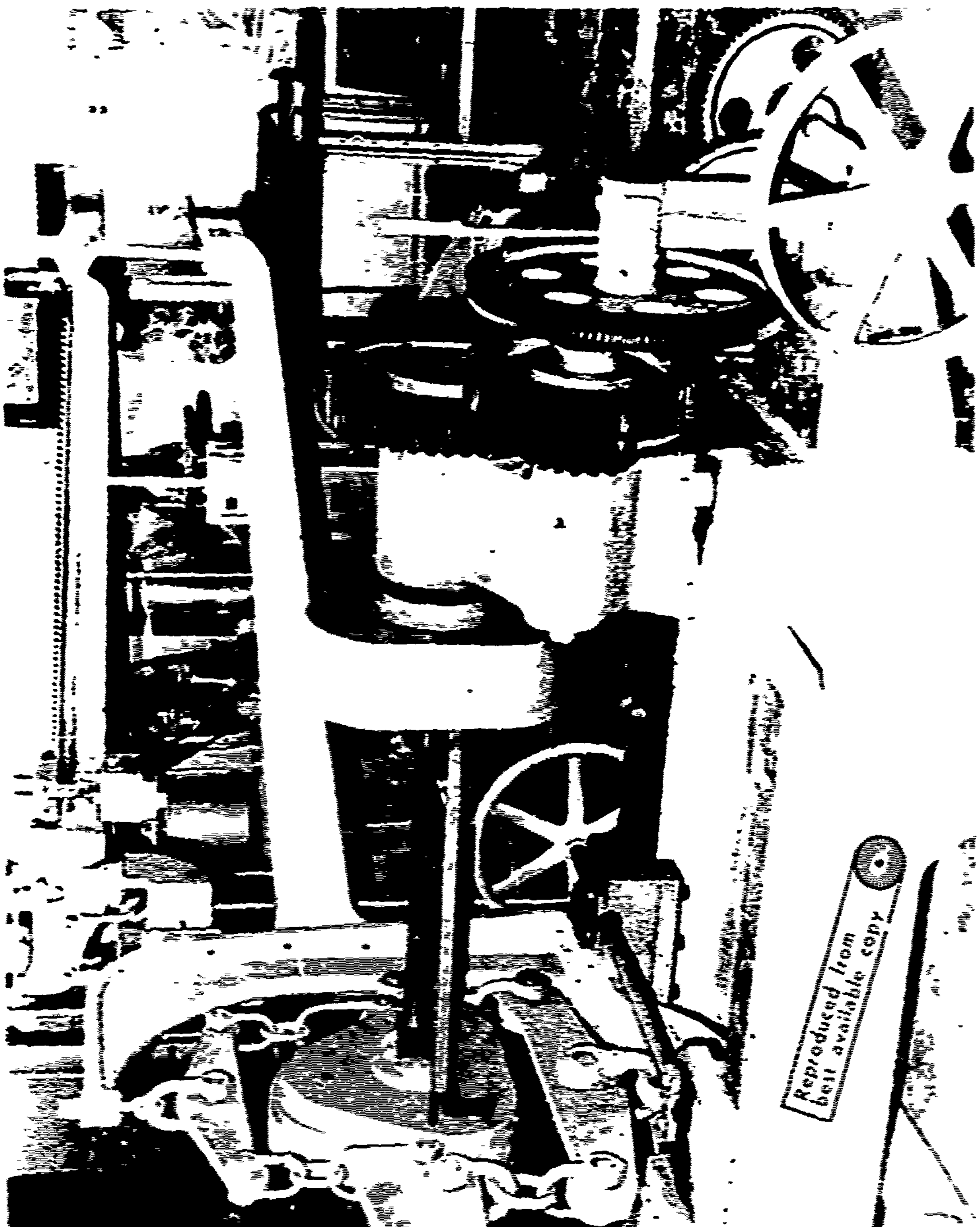


Figure 1. Deadweight Torsion Test Machine.

TABLE III. TEST SCHEDULE				
	Percent Load			
	With Lubrication			Nonlubrication
Set	1/2 Hr Run-In	1/2 Hr Run-In	1 Hr Run-In	30 Min (Max)
1	50	50	100	100
2	50	50	100	100
3	50	50	85	85
4	50	50	85	85
5	50	50	70	70
6	50	50	70	70

The run-in tests were used to determine temperature stabilization, wearing-in of the tooth profiles, and general system checkout. At the conclusion of these runs, the gear tooth surfaces were visually inspected to evaluate the surface condition.

GEAR STRESS CALCULATIONS

To maintain a consistent and accurate rating practice, most of the major aircraft companies and engine manufacturers use the American Gear Manufacturer's standards for strength rating. Although the AGMA gear rating formulas for strength and durability provide for the use of modifying factors to account for misalignment, dynamic conditions, overload conditions, size effect, etc., specific values for these factors as applicable to helicopter transmission gears do not exist. This requires a comparison of gear stresses with operational and test experience gained in previous design efforts.

The methods and/or experience currently being used for forecasting stress allowables and gear life in the design of helicopter transmission gearing cannot be applied directly for test specimens operating in gear research type test stands. The alignment, rigidity, dynamics, etc., of an R&D test stand act to improve the load capacity of the actual test specimens. Past experience with the Boeing-Vertol R&D test stand used for this program has indicated an increased load capacity for test gears (depending on gear type) in the range of 1.5 to 3.0

times the design allowables established for aircraft power gears. Consequently, it is not practical to establish a basic load level for test gears in the design stage for R&D operation in a test stand environment without relating these loads to standard design practice. Therefore, it must be expected that baseline configuration test gears will operate in an R&D test stand at stress levels above the 100-percent load level, which has been established for operation in an aircraft transmission, without failure.

The 100-percent design load for the test gear configurations utilized in this test program was established and defined as that load (10,000 inch-pounds pinion torque) which results in a bending stress of 31,400 pounds per square inch and a Hertz stress of 211,000 pounds per square inch, which is commensurate with current levels established for helicopter main power spiral bevel gears.

The test gear stress levels presented in this report were calculated by an existing Boeing-Vertol computer program based on the Gleason method and the following AGMA standards:

216.01 - Surface Durability (Pitting) Formulas for Spiral Bevel Gear Teeth

223.01 - Rating the Strength of Spiral Bevel Gear Teeth

AGMA Standard 223.01 rates the bending strength of spiral bevel gear teeth as follows:

$$St = \frac{Wt \times Ko}{Kv} \times \frac{Pd}{F} \times \frac{Ks \times Km}{J}$$

where St = calculated tensile stress at root of tooth in pounds per square inch

Wt = transmitted tangential load in pounds

Ko = overload factor

Kv = dynamic factor

Pd = diametral pitch at large end of tooth

F = face width in inches

Ks = size factor

Km = load distribution factor

J = geometry factor

For the test specimens in this program, assume that

$$Ko, Kv = 1.0$$

$$F = 1.426$$

$$Pd = 5.833$$

$J = 0.3067$ (calculated by computer program)

$$Ks = 0.6416$$

$$Km = 1.1$$

Therefore, the test specimen tensile stress is

$$St = \frac{Wt \times 1.0}{1.0} \times \frac{5.333}{1.426} \times \frac{0.6416 \times 1.1}{0.3067}$$

$St = \underline{9.421\ Wt}$ (see Figure 10)

AGMA Standard 216.01 rates the contact stress of spiral bevel gears as follows:

$$Sc = Cp \sqrt{\frac{Wt \times Co}{Cv} \times \frac{Cs}{dF} \times \frac{Cm \times Cf}{I}}$$

where Sc = calculated maximum contact stress in pounds per square inch

Cp = elastic coefficient (2,800 for steel)

Wt = transmitted tangential load at operating pitch diameter in pounds

Co = overload factor

Cv = dynamic factor

d = pinion operating pitch diameter in inches

F = face width in inches

Cs = size factor

Cm = load distribution factor

I = geometry factor

Cf = surface condition factor

For the test specimens used in this program, assume that

Co, Cv, Cs, Cf = 1.0

F = 1.426

Cm = 1.1

I = 0.0767 (calculated by computer program)

d = 6.00

Then,

$$Sc = 2800\sqrt{\frac{Wt \times 1.0}{1.0} \times \frac{1.0}{6.000 \times 1.426} \times \frac{1.1 \times 1.0}{0.0767}}$$

$$Sc = 2800\sqrt{\frac{1.1\ Wt}{0.6562}} \quad \text{(see Figure 11)}$$

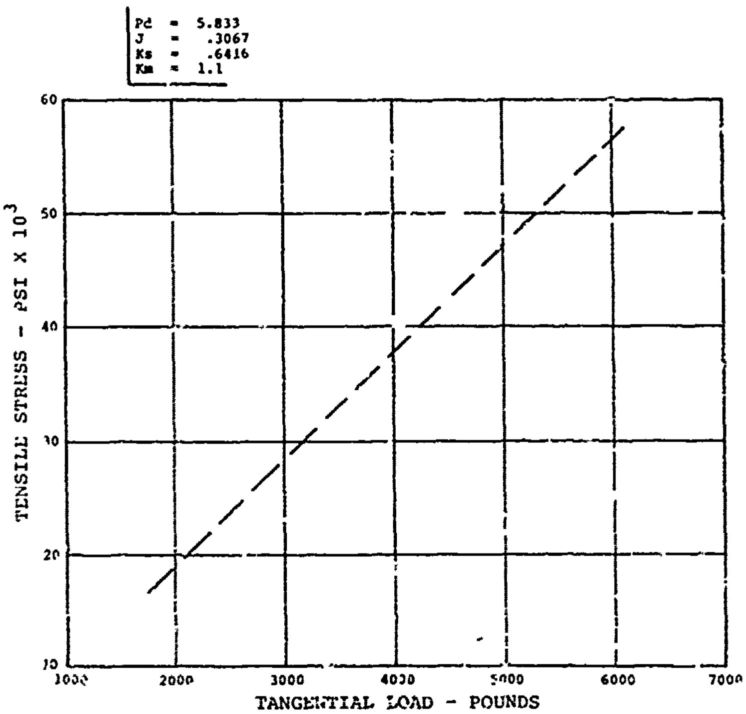


Figure 10. Tensile Stress in Spiral Bevel Test Gears.

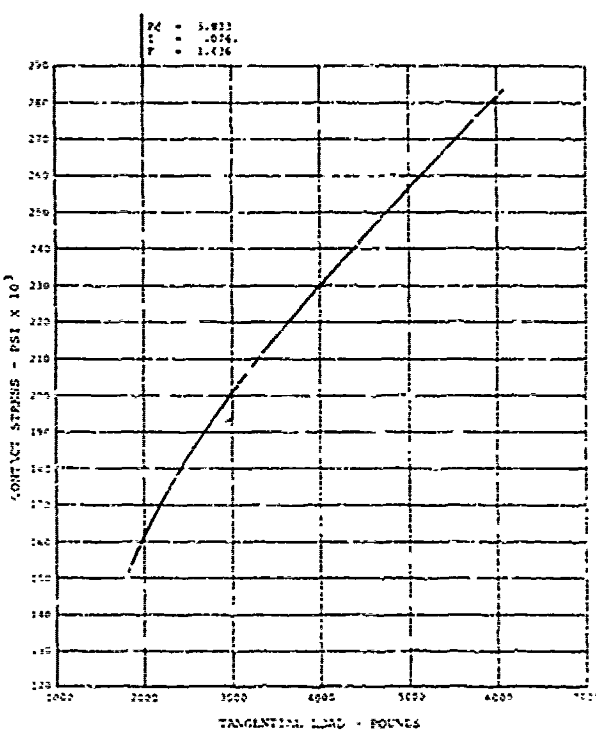


Figure 11. Contact Stress in Spiral Bevel Test Gears.

TEST RESULTS

DEFLECTION TEST

Analytical evaluation of the load-carrying capacity of bevel gears involves assumptions regarding the nature of the tooth bearing for the specific gear mountings under load. Unless these assumptions are relatively accurate, actual stresses may vary considerably from the calculated values, resulting in a possible life reduction.

During manufacture of bevel gears, the desired tooth contact pattern is established from observation of the pattern obtained under light load in a gear tooth pattern checker. It is possible by selection of grinding wheel diameters and grinding machine settings to vary the length, width, and position of a tooth bearing.

With gear mountings that are rigid, the behavior of the tooth bearing under load is usually more predictable. Consequently, it is usually possible to develop tooth bearing patterns which are based on previous experience. However, in the case of aircraft applications, the mounting designs are markedly different, in that rigidity is sacrificed in favor of weight reduction. Therefore, it is seldom possible to accurately predict, during the design stage, the type of tooth bearing required at no load in a tooth pattern checker in order to obtain the desired bearing pattern in the final gear mountings. A study of the mounting design and operating conditions together with a judgement based on experience must be used to establish the initial tooth bearing. From this point, the development of the final tooth bearing is accomplished by actual trial of the gears in their final mountings.

Tooth bearing pattern evaluations were made at the 50-percent and 100-percent load levels on the first set of baseline test gears. This was accomplished by applying rouge to the teeth of the pinion member, in several sectors, and rotating the gear set through mesh by hand. Results of this deflection test were considered to be satisfactory and are shown in Figure 12.

BOEING VERTOL Date 10/12/71

RECORD OF DEFLECTION TEST GEAR PATTERN

PART NO. GEAR SK23410-1 SERIAL NO. GEAR A102
PINION SK23409-1 PINION A102

NO. TEETH GEAR 43 HAND OF SPIRAL GEAR R/H
PINION 35 PINION L/H

SUMMARY NO. 146.656-1 BACKLASH TOTAL .012 - .014

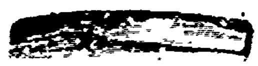
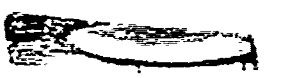
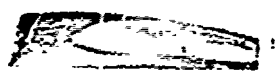
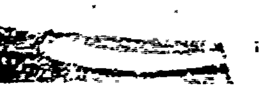
PERCENT LOAD		GEAR PATTERN	PINION PATTERN
0	D		
	D		
50	D		
	D		
100	D		
	D		

Figure 12. Deflection Test Gear Patterns.

TEST DATA

The objective of this experimental test program was to evaluate the material effect on performance of main power spiral bevel gears operating in a nonlubricated environment.

A summary of the test results is shown in Table IV, which contains the pertinent information obtained during the test phase, including part numbers, serial numbers, gear type, load levels, and test time.

Load Schedule

The basic 100-percent design load level for all of the test gears was established as 3333 pounds tangential load (10,000 inch-pounds pinion torque), resulting in a bending stress of 31,400 pounds per square inch and a contact stress of 211,000 pounds per square inch as calculated by the American Gear Manufacturers Association standards.

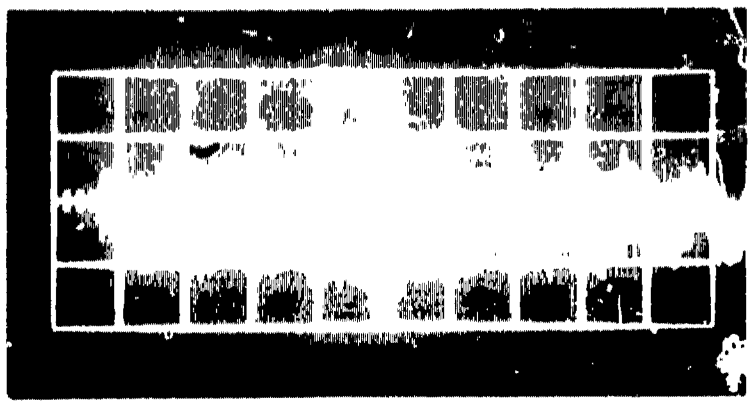
Each gear set was subjected to two consecutive runs at the 50-percent load level with lubrication, followed by a one-hour run at the specified load level with lubrication. At that time, the lubricating oil was shut off by a remote-controlled solenoid, and the test was continued for one-half hour maximum, with no lubrication to the test gear mesh. During each test run vibration surveillance was provided by visual observation of the oscilloscope traces (see Figure 13). Torque readings were taken immediately after the conclusion of the nonlubrication testing to determine the degree of torque loss. Figure 14 presents a summary of the torque losses for all nonlubrication testing.

Temperature Instrumentation

Temperature-sensitive gages were applied to the heel end of the spiral bevel test pinions (see Figure 15) in an attempt to record the blank temperature during the test runs, particularly in the nonlubricated testing. These gages were heat sensors, on a plate, with self-adhesive and hermetically sealed heat-sensitive elements which change chemical structure at given calibrated temperatures. Two individual plates were used on each test pinion in the following ranges: 230°F, 240°F, 250°F, 260°F and 350°F, 400°F, 450°F, 500°F. Prior to installation on the gears, several bench tests were conducted

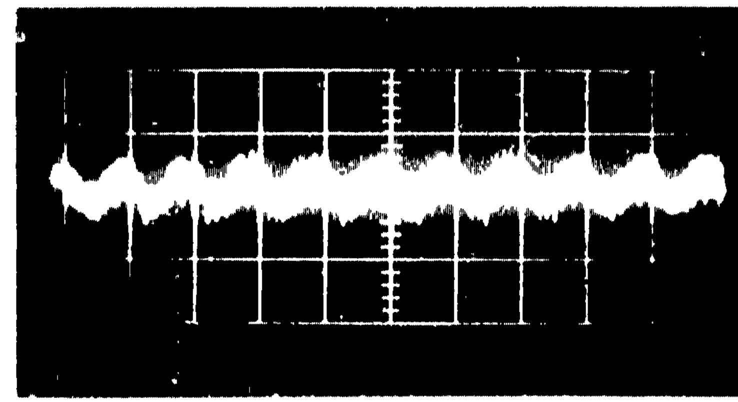
TABLE IV. GEAR SPECIMEN DATA				
Run Number/ Material	Load (percent)	Pinion (s/n)	Gear (s/n)	Nonlubr. Run Time (minutes)
1/9310	100	A102	A102	25
2/9310	100	A103	A103	13.5
3/VASCO	100	A101	A102	25
4/VASCO	100	A104	A106	19
5/9310	85	A106	A105	30
6/VASCO	85	A106	A107	17
7/9310	85	A106	A106	30
8/VASCO	85	A109	A109	30
9/9310	75	A107	A107	30
10/VASCO	75	A110	A110	30
11/9310	75	A108	A108	30
12/VASCO	75	A112	A113	30

BASELINE GEAR SET 1 AT 100-PERCENT LOAD

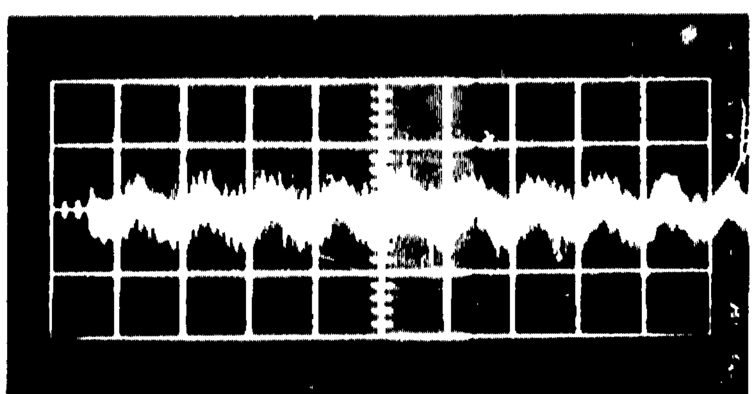


Minutes Nonlubrication

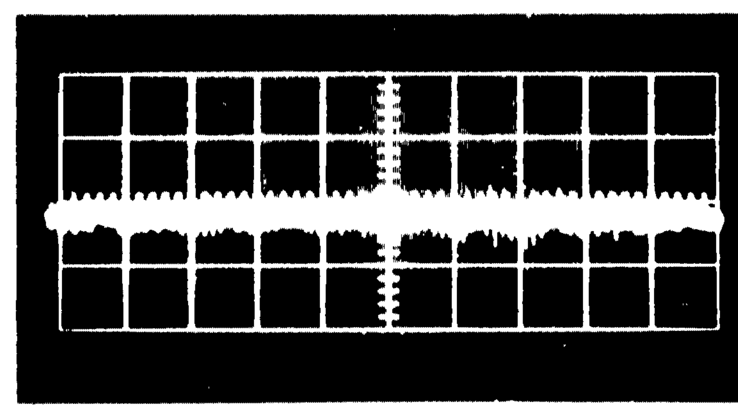
VASCO X2 GEAR SET 4 AT 85-PERCENT LOAD



30 Minutes Nonlubrication



0 Minutes Nonlubrication



1 Minute Nonlubrication

Figure 13. Vibration Signature Response of Test Gears.

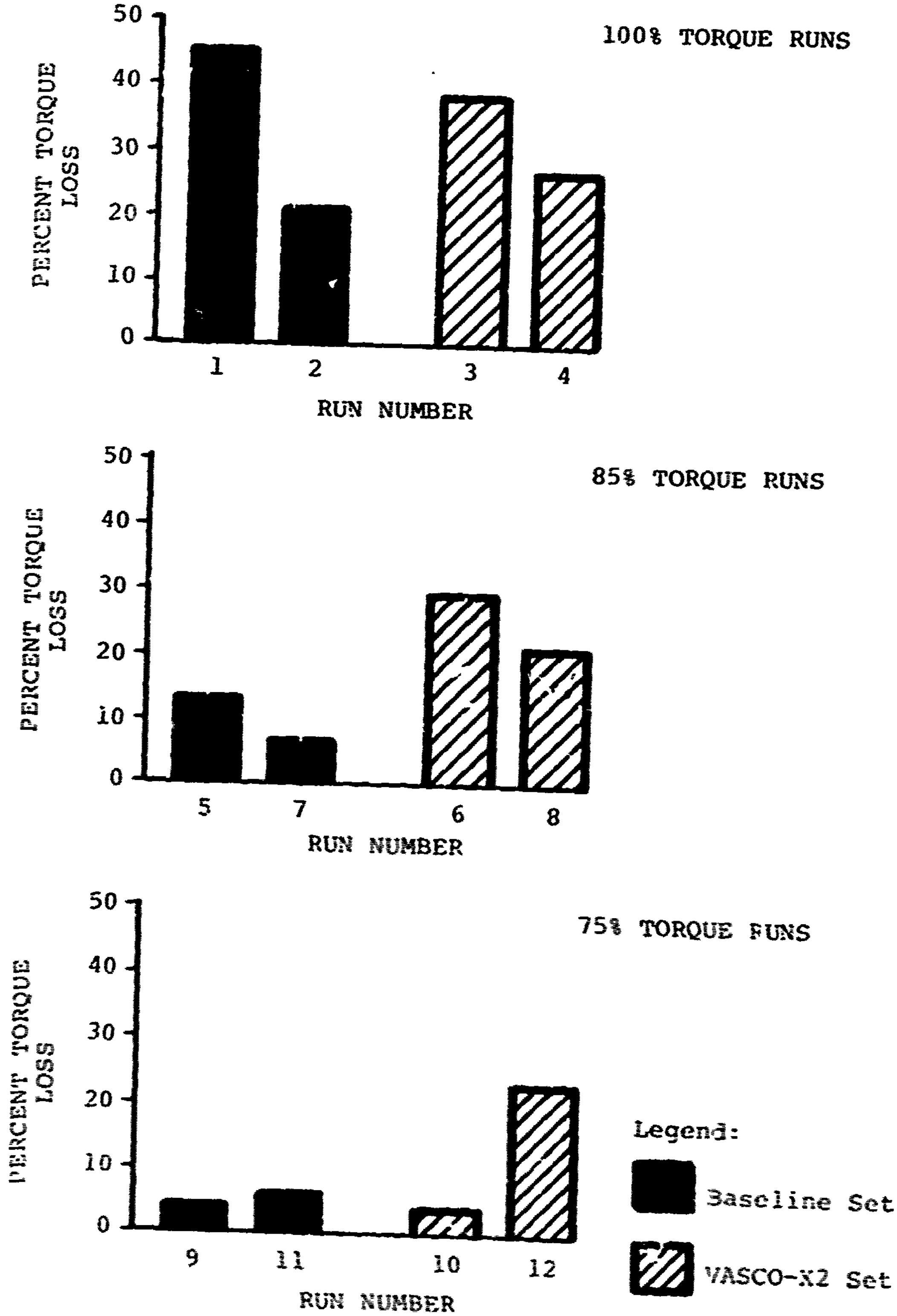


Figure 14. Torque Losses in Nonlubrication Testing.

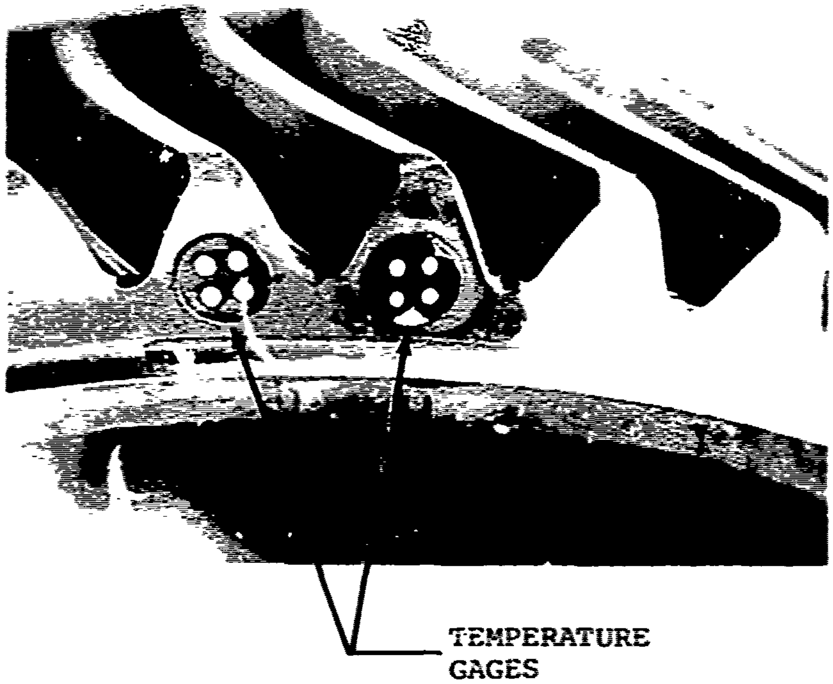


Figure 15. Temperature Gage Installation.

with 400°F MIL-L-7808 lubricating oil to select a protective coating for the temperature gages. Results of this experiment indicated that M-BOND 610 gage cement would provide the most protection for the gages against the lubricating oil. However, during the actual testing, the gages either turned completely black or were removed during nonlubrication testing.

Temperature-sensitive crayons were used as a backup method for recording gear-blank temperatures at the end of the nonlubrication tests. The crayons were applied directly to the gear teeth through the inspection cover at the conclusion of the nonlubrication testing, and the results were recorded. During the second baseline run, verification of the temperature evaluation of the crayons was provided by using an external pyrometer, which indicated approximately the same temperature as the crayons.

Gear Testing

Twelve sets of spiral bevel gears were run on the test stand: six sets of baseline test gears (AISI 9310 steel) and six sets of VASCO-X2 test gears.

Baseline Test Gears - Each set consists of a pinion, part number SK23410-1, and a gear, part number SK23410-1. All components were numbered serially:

Set No. 1 is pinion A102 with gear A102
Set No. 2 is pinion A103 with gear A103
Set No. 3 is pinion A105 with gear A105
Set No. 4 is pinion A106 with gear A106
Set No. 5 is pinion A107 with gear A107
Set No. 6 is pinion A108 with gear A108

VASCO-X2 Test Gears - Each set consists of a pinion, part number SK23411-1, and a gear, part number SK23412-1. All components were numbered serially:

Set No. 1 is pinion A101 with gear A102
Set No. 2 is pinion A104 with gear A106
Set No. 3 is pinion A106 with gear A107
Set No. 4 is pinion A109 with gear A109
Set No. 5 is pinion A110 with gear A110
Set No. 6 is pinion A112 with gear A113

Testing was conducted in accordance with the load schedule. The test procedure and the principal results are given in Table V for the baseline gears and in Table VI for the VASCO-X2 gears.

Run-in testing was done at the 50-percent load level. Visual inspections of the tooth surfaces were conducted at the conclusion of each run-in test. Results of these inspections indicated no evidence of surface distress or damage. The load runs were conducted at increased loads: 75 to 100 percent (see Tables V and VI).

The nonlubrication testing was conducted by shutting off the oil supply to the gear mesh in the middle of a load run and continuing the load run until there was a significant growth in the vibration signature. A rapid increase in vibration (to a level more than two and a half times the level noted at the beginning of nonlubrication testing) constituted a failure, and the test run was ended. This criterion was developed as a result of testing the first baseline gear set, and it was used for all the remaining tests. Vibration data are given in Tables VII and VIII. Thermochrom crayon temperatures are given in Tables IX and X.

Pinion-blank temperatures and torque losses (given in Table XI) were checked after each test within minutes of shutdown. Torque losses are attributed to the damage and subsequent wearing away of material from the contacting gear tooth profiles.

At the conclusion of the nonlubrication testing, the tooth surfaces of both members (pinion and gear) were given a visual inspection. Photographs showing the final condition of the tooth surfaces are given in Figures 16 and 17.

Baseline Gear Set Number 1 - At the end of the run-in tests, the temperature gages were not exposed. After 20 minutes of nonlubrication testing, the vibration signal grew to approximately four times the signal seen at the start of the test run, and the test was ended. The rapid growth in vibration signal occurred in a very short time (seconds), indicating the need for constant visual surveillance of the oscilloscope. Visual inspection of the gear tooth surfaces at the end of nonlubrication testing revealed severe scoring and metal flow, heat discoloration, and pitchline pitting, but no cracks. Metal was transferred from the tips of the teeth on the drive side and

TABLE V. TESTING OF BASELINE TEST GEARS

Elapsed Time (minutes)	BASELINE SET 1 Oil Pressure[1] (psi)	Oil Temp In/Out (°F)	Vibration Trace[2] (cm)	BASELINE SET 2 Oil Pressure[1] (psi)	Oil Temp In/Out (°F)	Vibration Trace[2] (cm)	BASELINE SET 3 Oil Pressure[1] (psi)	Oil Temp In/Out (°F)	Vibration Trace[2] (cm)
RUN IN: 50-PERCENT LOAD WITH LUBRICATION									
0	54	190/187	.40	55	190/191	.9	57	195/190	.8
15	55	190/191	.40	56	192/189	.9	53	192/191	.8
20	55	190/192	.40	56	192/189	.9	55	194/197	.8
30	55	190/192	.40	56	192/192	.9	55	195/194	.8
shut down and inspect									
30	55	190/187	.40	58	185/187	.8	61	192/190	.8
40	55	190/192	.40	58	190/190	.8	57	195/195	.8
50	55	190/195	.40	58	190/191	.8	58	195/200	.8
60	55	190/195	.40	55	195/200	.8	57	200/200	.8
shut down and inspect									
LOAD RUN:	130-PERCENT LOAD			100-PERCENT LOAD			85-PERCENT LOAD		
0	54	187/188	.40	55	195/195	.8	55	200/200	.8
15	55	185/195	.40	55	197/205	.8	55	200/205	.6
30	55	187/195	.40	55	200/205	.5	55	198/201	.7
45	55	187/192	.40	55	200/205	.4	55	197/203	.7
60	55	187/192	.40	55	195/205	.4	55	200/203	.7
UNLUBRICATION: SHUT OFF OIL JET TO MAIN GEAR MESH, BUT LET TEST STAND RUN									
60	55	187/192	.40	55	195/207	.4	56	198/201	.7
65	55	185/204	.44	-	-	-	-	-	-
70	55	185/204	.44	45	195/215	1.5	57	191/210	.8
75	-	-	-	50	195/217	1.4	-	-	-
80	55	185/227	2.8	-	-	-	57	192/209	.9
85	55	185/220	2.2	-	-	-	-	-	-
90	-	-	-	-	-	-	53	192/219	.9
	BASELINE SET [illegible]			BASELINE SET [illegible]			BASELINE SET 4		
RUN IN: 50-PERCENT LOAD WITH LUBRICATION									
0	50	200/195	.8	55	193/190	.8	55	183/173	.6
15	55	205/195	.8	50	185/182	.8	55	195/182	.6
20	55	205/197	.8	56	190/190	.3	55	195/201	.6
30	55	205/210	.8	55	210/205	.8	56	197/193	.6
shut down and inspect									
30	54	203/200	.8	55	200/201	.8	55	195/193	.6
40	55	205/208	.8	55	200/208	.8	55	195/195	.6
50	55	208/210	.8	55	200/208	.8	56	195/195	.6
60	55	205/210	.8	55	197/195	.8	55	195/195	.6
shut down and inspect									
LOAD RUN:	85-PERCENT LOAD			75-PERCENT LOAD			75-PERCENT LOAD		
0	55	201/202	.6	60	195/195	.6	55	195/195	.6
15	55	200/208	.6	55	195/197	.6	55	195/195	.6
30	55	200/208	.6	55	195/200	.6	55	195/197	.6
45	55	197/202	.6	55	195/201	.6	55	195/199	.6
60	55	197/202	.7	55	195/201	.6	55	195/199	.6
UNLUBRICATION: SHUT OFF OIL JET TO MAIN GEAR MESH, BUT LET TEST STAND RUN									
60	55	197/202	.7	60	195/201	.6	55	195/199	.6
65	-	-	-	-	-	-	-	-	-
70	57	195/207	.9	59	192/201	.8	62	192/205	.9
75	-	-	-	-	-	-	-	-	-
80	57	195/209	1.0	59	195/214	1.0	62	190/205	.8
85	-	-	-	-	-	-	-	-	-
90	57	195/210	.9	58	195/210	.9	62	190/205	.6

1. Oil pressure taken at the inlet to the test box.
2. Vibration data taken from oscilloscope trace measured peak-to-peak "double amplitude". Scale, 0.5 volt per centimeter.

TABLE VI. TESTING OF VASCO-X2 TEST GEARS

Elapsed Time (minutes)	VASCO SET 1 Oil Pressure[1] (psi)	Oil Temp In/Out (°F)	Vibration Trace[2] (cm)	VASCO SET 2 Oil Pressure[1] (psi)	Oil Temp In/Out (°F)	Vibration Trace[2] (cm)	VASCO SET 3 Oil Pressure[1] (psi)	Oil Temp In/Out (°F)	Vibration Trace[2] (cm)
[illegible] LOAD WITH LUBRICATION									
[illegible]	[illegible]	[illegible]	[illegible]	55	[illegible]	[illegible]	55	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	55	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Shut down and inspect									
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Shut down and inspect									
LOAD RUN:	[illegible]-PERCENT LOAD			[illegible]-PERCENT LOAD			[illegible]-PERCENT LOAD		
[illegible]	[illegible]	[illegible]	[illegible]	55	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	55	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	55	[illegible]	[illegible]	55	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	55	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	55	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
UNLUBRICATED: SHUT OFF OIL JET TO MAIN GEAR MESH, BUT LET TEST STAND RUN									
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	-	-	-	-	-	-	-	-	-
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	-	-	-		end of test			end of test	
[illegible]	[illegible]	[illegible]	[illegible]						
[illegible]		end of test							
[illegible]									
	VASCO SET 4			VASCO SET 5			VASCO SET 6		
[illegible] LOAD WITH LUBRICATION									
[illegible]	55	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	55	[illegible]	[illegible]
[illegible]	55	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	55	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	55	[illegible]	[illegible]	55	[illegible]	[illegible]
[illegible]	55	[illegible]	[illegible]	55	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Shut down and inspect									
[illegible]	55	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	55	[illegible]	[illegible]	55	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	55	[illegible]	[illegible]	55	[illegible]	[illegible]	55	[illegible]	[illegible]
[illegible]	55	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	55	[illegible]	[illegible]
Shut down and inspect									
LOAD RUN:	[illegible]-PERCENT LOAD			[illegible]-PERCENT LOAD			[illegible]-PERCENT LOAD		
[illegible]	55	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	55	[illegible]	[illegible]
[illegible]	55	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	55	[illegible]	[illegible]
[illegible]	55	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	55	[illegible]	[illegible]
[illegible]	55	[illegible]	[illegible]	55	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	55	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
UNLUBRICATED: SHUT OFF OIL JET TO MAIN GEAR MESH, BUT LET TEST STAND RUN									
[illegible]	55	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	-	-	-	-	-	-	-	-	-
[illegible]	-	-	-	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	55	[illegible]	[illegible]	-	-		-	-	
[illegible]	-	-		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	-			-	-	-	-	-	-
[illegible]	55	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

1. Oil pressure taken at the inlet to the test box.
2. Vibration data taken from oscilloscope trace measured peak-to-peak (double amplitude). Scale, [illegible] mil per centimeter.

TABLE VII. VIBRATION DATA FROM NONLUBRICATION TESTING OF BASELINE GEARS

Elapsed Time (minutes)	Vibration Trace* (cm)	Comments
Baseline Set 1		
-	-	No data
Baseline Set 2		
0	.6	-
1.0	.2+	. . . Rise from test stand
2.4	.4	. . . High-frequency rise; No wave in trace
3.6	.6	. . . Wave trace; increased rise
6.3	.8	. . . Sawtooth wave trace; higher pitch rise
9.8	.9	-
10.9	1.0	-
11.8	1.2	-
12.3	1.4	-
13.5	Increasing	Shut down
Baseline Set 3		
0.6	1.0	-
1.2	.8	-
2.	.6	-
3.	.6	-
4.	1.0	-
6.	.8	-
7.	.9	-
10.	.8	-
11.	.9	-
14.	.8	-
16.	.9	-
17.	.8	-
18.	.9	-
19.	.8	-
20.	.8	-
Baseline Set 4		
1-5	.6	-
6-10	.6	-
11	1.0	-
12	1.1	-
13-18	.9	-
19-21	1.0	-
24-26	.9	-
28	1.0	-
30	.9	-
Baseline Set 5		
0-3	.8	-
[illegible]	[illegible]	
8-11	[illegible]	
12	1.0	-
13-19	[illegible]	-
20	[illegible]	
21-30	[illegible]	
Baseline Set 6		
[illegible]	[illegible]	-
[illegible]	[illegible]	
[illegible]	[illegible]	-
[illegible]	[illegible]	
[illegible]	[illegible]	
29-30	[illegible]	-

*Vibration data taken from oscilloscope trace measured peak-to-peak absolute amplitude. Scale, 0.1 unit per centimeter.

TABLE VIII. VIBRATION DATA FROM NONLUBRICATION TESTING OF VASCO-X2 GEARS

Elapsed Time (minutes)	Vibration Trace* (cm)	Comments
VASCO Set 1		
1	.5	-
1.7	.4	-
3.0	.4	-
8.0	.5	. . . Pitch change
8.8	.6	-
15.5	.6	. . . Sawtooth signature
16.0	.8	. . . Pitch change
17.8	.8	. . . Sawtooth signature
18.0	.9	-
18.7	1.2	. . . Pitch change
20.6	1.4	-
VASCO Set 2		
1.6	.5	-
3.0	.5	-
7.0	.5	. . . Pitch change
7.7	.6	-
11.0	.6	-
12.8	.6	-
14.0	.6	. . . Pitch change
15.8	.8	. . . Sawtooth signature
16.8	1.2	. . . Pitch change
17.8	1.6	-
19.2	2.0	. . . End of test
VASCO Set 3		
1.8	.5	-
3.0	.7	-
6.0	.6	-
7.8	.3	-
10.0	.4	-
15.0	.8	. . . Pitch change
16.0	.9	-
17.0	1.9	. . . Growing rapidly
17.1	End of test	
VASCO Set 4		
1	.2	-
2	.3	-
3	.4	-
4	.5	-
5-15	.6	-
16-21	.8	-
22-25	.9	-
26	1.0	-
27	1.0	-
28	1.1	-
29-30	1.2	-
VASCO Set 5		
[illegible]	[illegible]	-
[illegible]	[illegible]	-
[illegible]	[illegible]	. . . Pitch change
[illegible]	[illegible]	Sawtooth signature
[illegible]	[illegible]	-
[illegible]	[illegible]	-
VASCO Set 6		
[illegible]	[illegible]	-
[illegible]	[illegible]	-
[illegible]	[illegible]	Sawtooth signature
[illegible]	[illegible]	-
[illegible]	[illegible]	Pitch change
[illegible]	[illegible]	-
30	[illegible]	-

*Vibration data taken from oscilloscope trace measured peak-to-peak absolute amplitude. Scale, 0.1 unit per centimeter.

TABLE IX. THERMOCHROM CRAYON TEMPERATURES OF BASELINE TEST GEARS AT CONCLUSION OF NONLUBRICATION TESTING

Thermochrom Crayon Temperature (°F)	Baseline Set 1 Time	Baseline Set 1 Response	Baseline Set 2 Time	Baseline Set 2 Response	Baseline Set 3 Time	Baseline Set 3 Response	Baseline Set 4 Time	Baseline Set 4 Response	Baseline Set 5 Time	Baseline Set 5 Response	Baseline Set 6 Time	Baseline Set 6 Response
124	No data		12:1[illegible]:40	No	1:41:45	No	-	No	12:04:50	No	5:15:15	No
11[illegible]			12:17:10	No	1:41:50	No	-	No	12:05:00	No	5:16:20	No
9[illegible]			12:18:1[illegible]	No	1:41:55	No	-	No	12:05:05	No	5:16:25	No
8[illegible]			12:18:2[illegible]	Partial	1:42:05	No	-	No	12:05:10	No	5:16:30	No
[illegible]			12:18:35	Yes	1:42:15	No	-	No	12:05:20	No	5:16:35	No
[illegible]			12:19:[illegible]	Yes	1:42:25	No	-	No	12:05:30	No	5:16:40	No
66			12:19:20	Yes	1:42:30	No	-	No	12:05:40	No	5:16:45	No
6[illegible]			12:19:35	Yes	1:42:40	No	-	No	12:05:50	No	5:17:00	Partial
5[illegible]			-	-	1:42:50	Partial	-	Partial	12:05:55	No	5:17:10	Partial
54			-	-	1:43:1[illegible]	No	-	No	12:06:10	No	5:17:15	Yes
4[illegible]			-	-	1:43:2[illegible]	Yes	-	Yes	12:06:15	No	5:17:20	Yes
[illegible]			-	-	1:43:25	Yes	-	Yes	12:06:25	No	5:17:25	Yes
[illegible]			-	-	-	-	-	-	12:06:35	No	-	-
[illegible]			-	-	-	-	-	-	12:06:50	Yes	-	-
2[illegible]			-	-	-	-	-	-	12:07:00	Yes	-	-

TABLE X. THERMOCHRON CRAYON TEMPERATURES OF VASCO-X2 TEST GEARS AT CONCLUSION OF NONLUBRICATION TESTING

Thermochrom Crayon Temperature (°F)	VASCO Set 1		VASCO Set 2		VASCO Set 3		VASCO Set 4		VASCO Set 5		VASCO Set 6	
	Time	Response	Time	Response	Time	Response	Time	Response	Time	Response	Time	Response
1240	11:58:05	No	12:23:40	No	12:38:15	No	3:57:00	No	6:18:55	No	6:27:55	No
1090	11:58:15	No	12:24:00	No	12:38:20	No	3:57:05	No	6:19:05	No	6:28:00	No
930	11:58:30	No	12:24:10	No	12:38:25	Partial	3:57:10	No	6:19:10	No	6:28:05	No
840	11:58:40	No	12:24:20	No	12:38:30	Yes	3:57:15	Partial	6:19:18	No	6:28:10	No
788	11:58:45	Yes	12:24:30	No	12:38:40	Yes	3:57:20	Yes	6:19:27	No	6:28:15	Yes
710	11:58:55	No	12:24:40	No	12:38:45	Yes	3:57:30	Yes	6:19:35	No	6:28:20	Yes
662	11:59:00	Yes	12:24:50	Yes	12:38:50	Yes	3:57:35	Yes	6:19:45	No	6:29:25	Yes
610	11:59:20	Yes	12:25:00	Partial	-	-	3:57:40	Yes	6:19:55	No	6:28:30	Yes
570	-	-	12:25:20	Yes	-	-	3:57:45	Yes	6:20:00	No	6:28:35	Yes
540	-	-	12:25:30	Yes	-	-	-	-	6:20:10	No	-	-
430	-	-	-	-	-	-	-	-	6:20:22	Yes	-	-
390	-	-	-	-	-	-	-	-	6:20:38	Yes	-	-
350	-	-	-	-	-	-	-	-	6:20:45	Yes	-	-
300	-	-	-	-	-	-	-	-	-	-	-	-
250	-	-	-	-	-	-	-	-	-	-	-	-

TABLE XI. OBSERVED DATA FROM NONLUBRICATION TESTING

Set	Load (percent)	Duration (minutes)	Pinion-Blank Temperatures (°F)	Torque Loss (percent)
<u>Baseline Test Gears</u>				
1	100	25.0	650 to 1000	44.5
2	100	13.5	788 to 840	21.0
3	85	30.0	430 to 570	13.0
4	85	30.0	430 to 570	30.0
5	75	30.0	250 to 300	4.0
6	75	30.0	540 to 570	6.0
<u>VASCO-X2 Test Gears</u>				
1	100	25.0	660 to 770	38.0
2	100	19.0	570 to 660	27.0
3	85	17.0	840 to 930	29.0
4	85	30.0	788 to 844	21.0
5	75	30.0	390 to 430	4.0
6	75	30.0	710 to 788	22.0

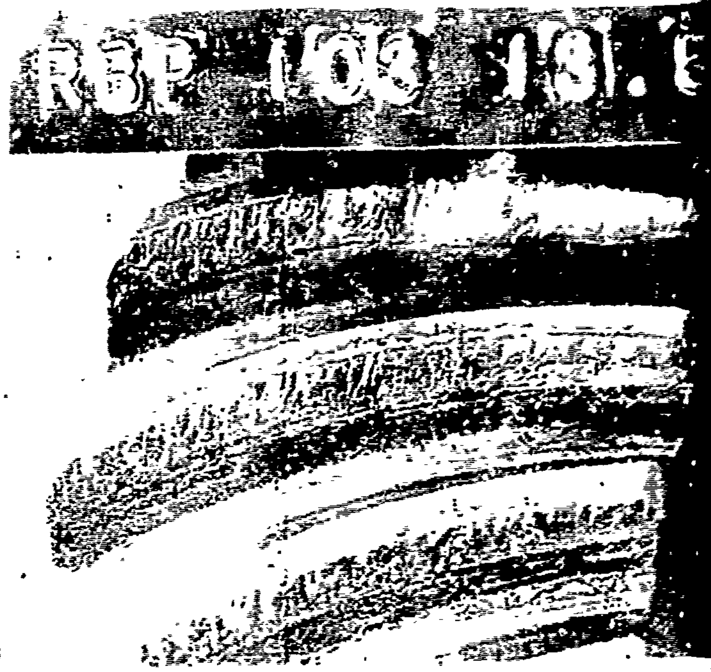
deposited in the fillet root in the form of a metal fin on practically every tooth of the pinion member. The gear member was also heavily scored, but to a somewhat lesser degree than the pinion, with heavy wear indications at the toe end of the driven side. A great deal of metal debris was found in the test housing. This debris was in the form of slivers and splinters. The connecting cross-shaft to the slave bevel gearbox developed heat color stains of light blue, violet, brown, and amber, in that order, coming away from the test gear mesh. Heat stains of comparable colors on 4340 steel (the shaft material) usually indicate a temperature of 650°F to 750°F.

Disassembly of the test pinion was difficult due to ovality of the mounting holes. In addition, several areas indicated the initial stage of welding the bolts to the mounting holes.

BASELINE GEAR SET 1

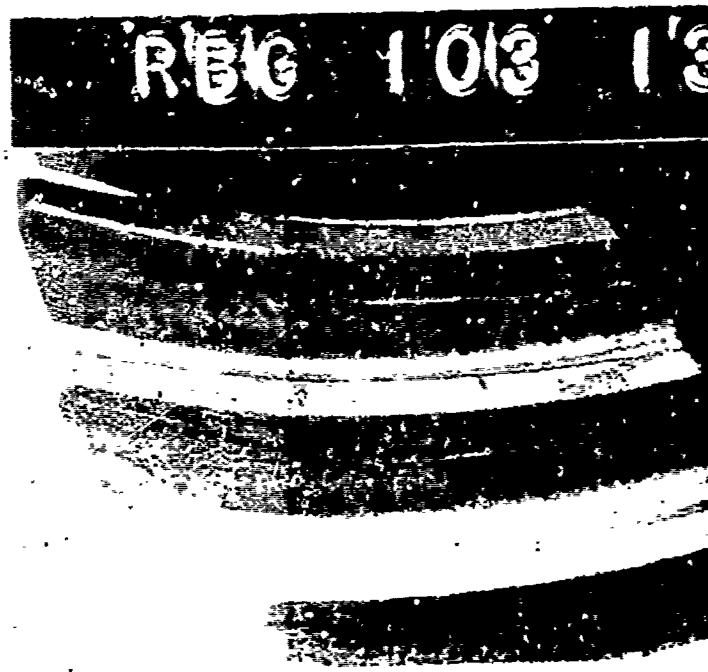
BASELINE GEAR SET 2

Pinion Number A102



Pinion Number A103

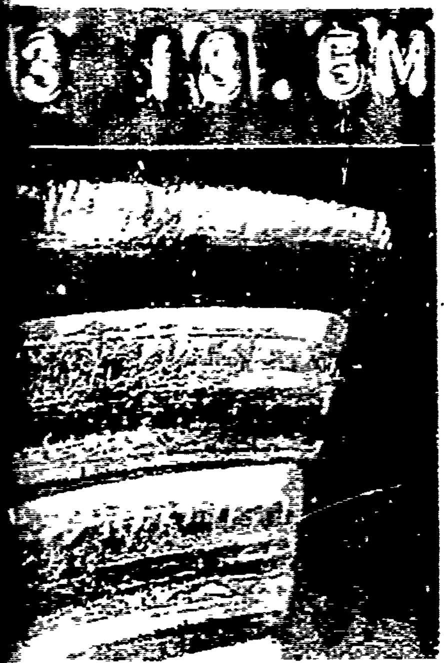
Gear Number A102



Gear Number A103

Figure 16. Final Condition of Baseline Test Gears (AISI 9310 Steel) After Nonlubrication Testing (Sheet 1 of 2).

GEAR SET 2



Number A103

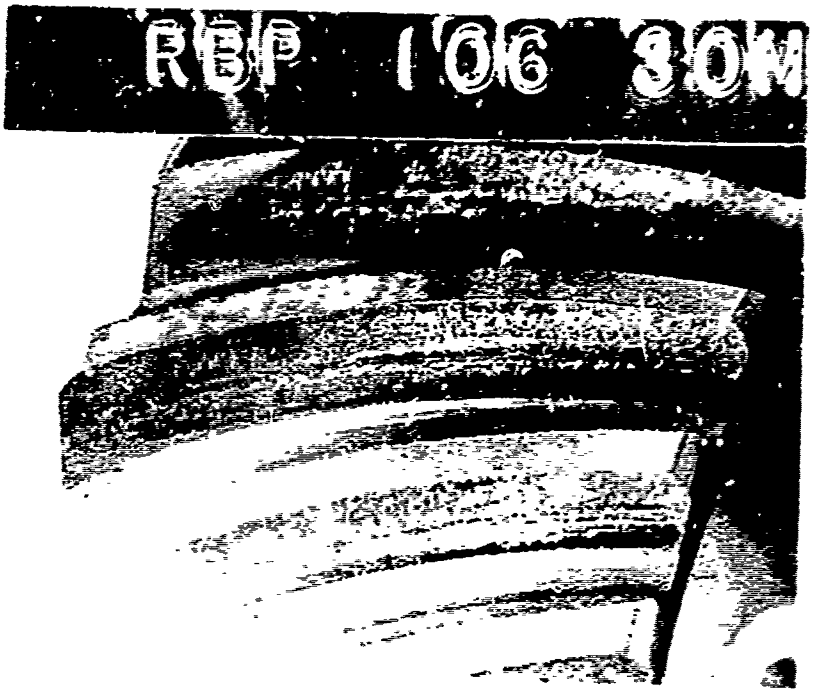
mber A103

BASELINE GEAR SET 3

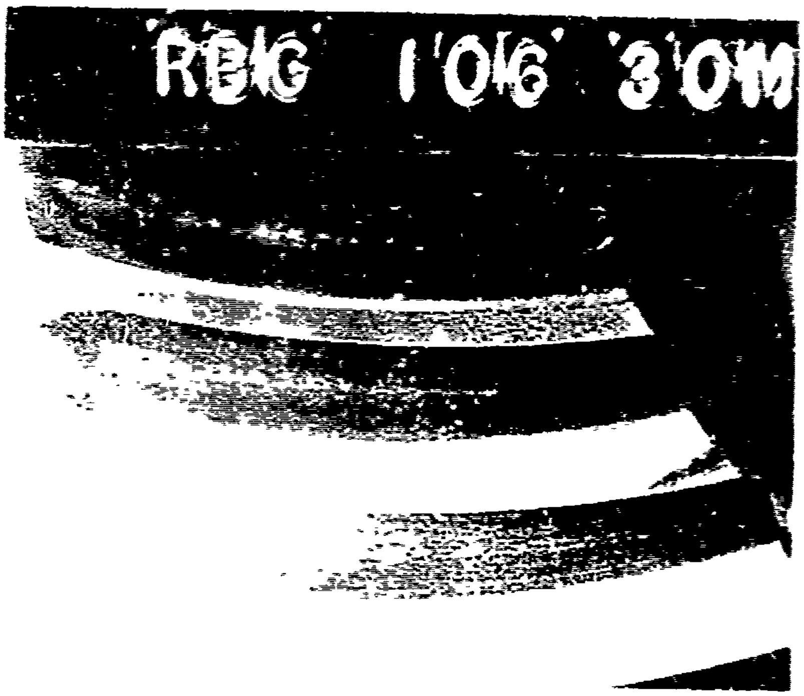
Pinion Number A105

Gear Number A105

BASELINE GEAR SET 4



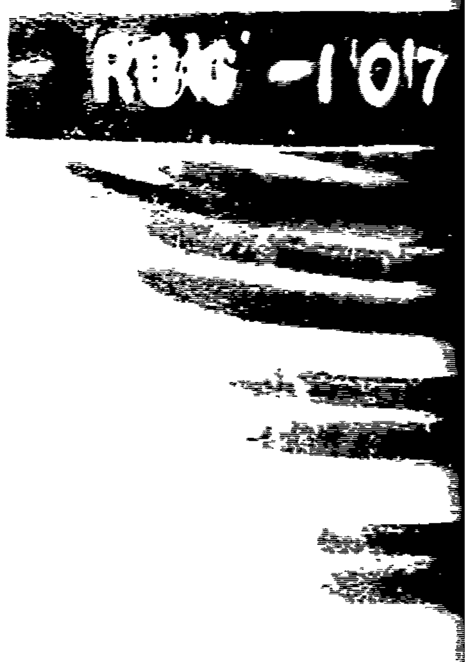
Pinion Number A106



Gear Number A106

BASELINE GEA

Pinion Numbe



Gear Number

Figure 16 - Continued (Sheet 2 of 2).

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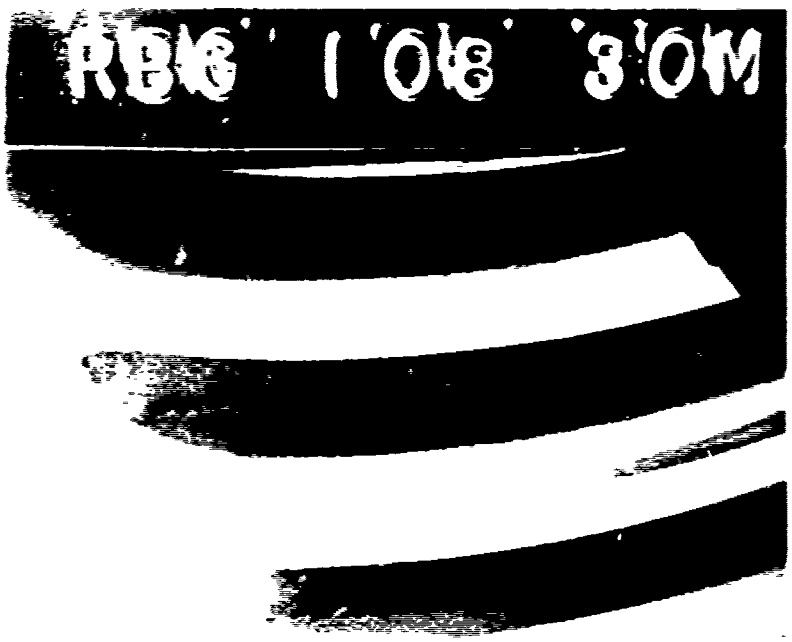
SELINE GEAR SET 5

BASELINE GEAR SET 6

ion Number A107

Pinion Number A108

ar Number A107

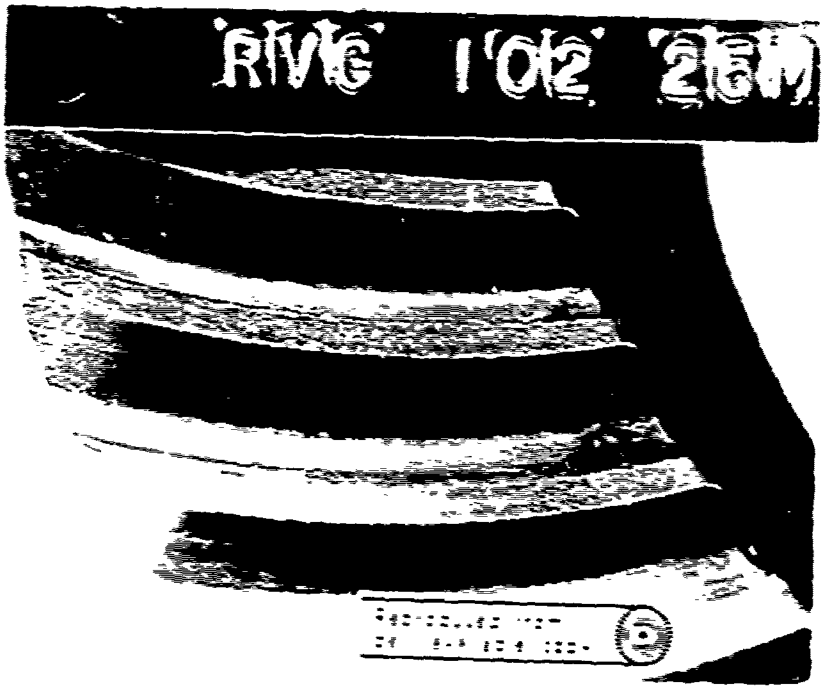


Gear Number A108

B

VASCO-X2 GEAR SET 1

Pinion Number A101



Gear Number A102

NOTE: GEAR SET NO. 2 IS SHOWN IN SHEET 2 OF THIS FIGURE.

Figure 17. Final Condition of VASCO-X2 Steel Gears After Nonlubrication Testing (Sheet 1 of 2).

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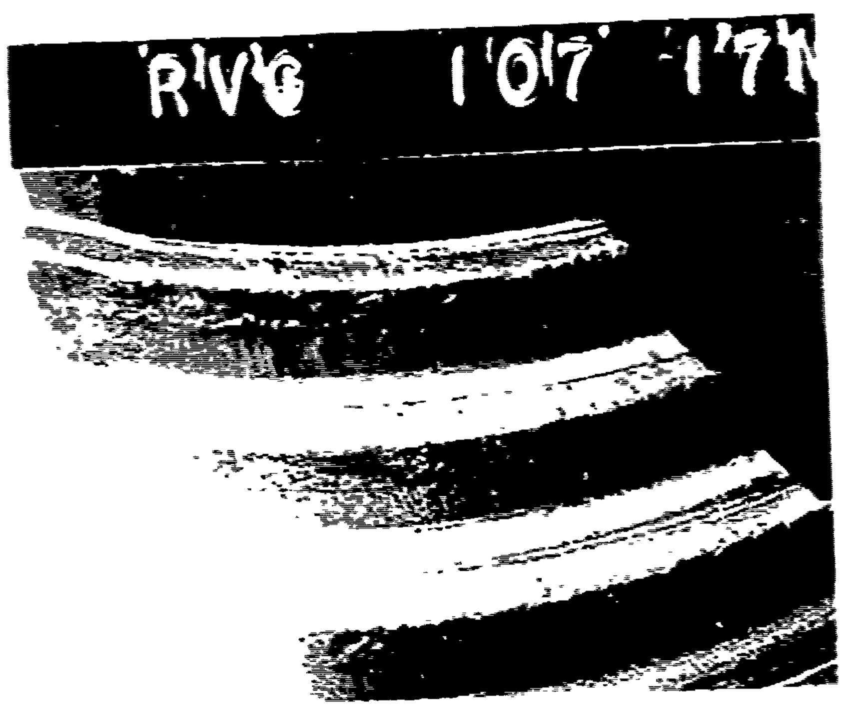
VASCO-X2 GEAR SET 3

Pinion Number A106

T NO. 2
EET 2



Gear Number A107

B

VASCO-X2 GEAR SE

Pinion Number A104

Pinion Number A1

Gear Number A106

Figure 17 - Continued (Sheet 2 of 3).

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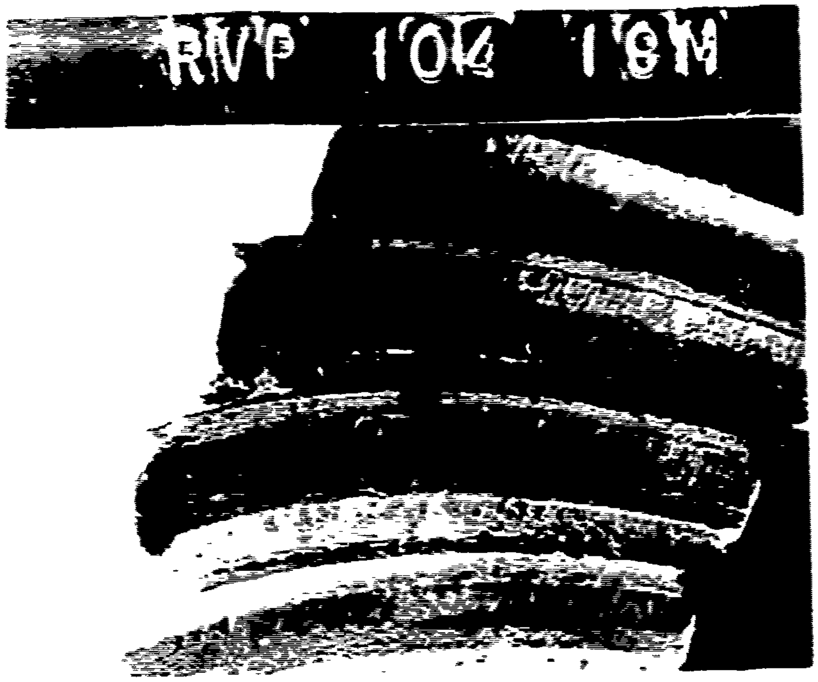
SCO-X2 GEAR SET 2

inion Number A104

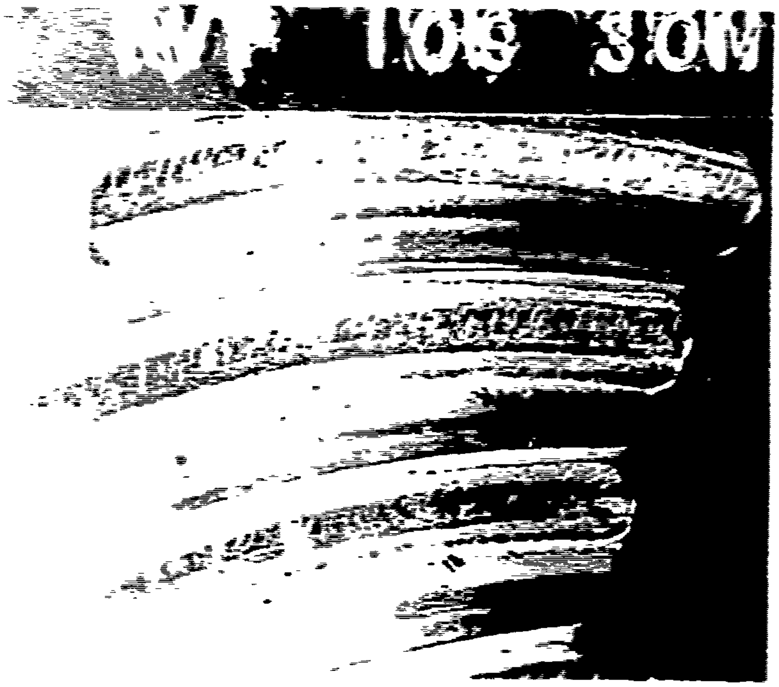


Pinion Number A104

Gear Number A106

B

VASCO-X2 GEAR SET 4

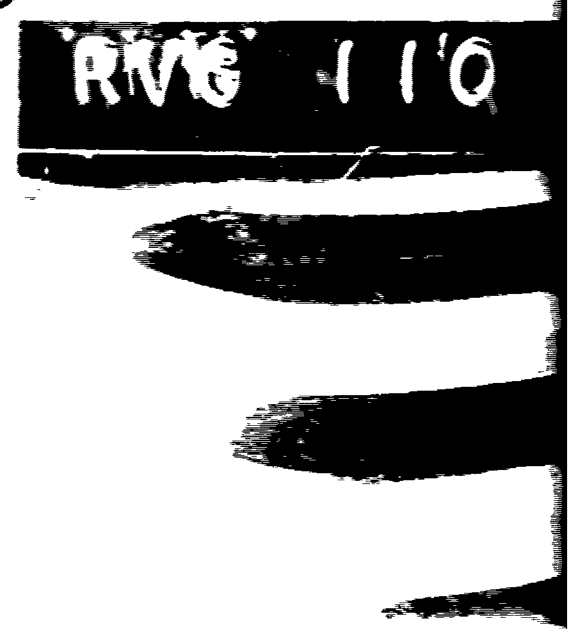


Pinion Number A109

VASCO-X2 GEAR SE

Pinion Number A1

Gear Number A109



Gear Number A110

Figure 17 - Continued (Sheet 3 of 3).

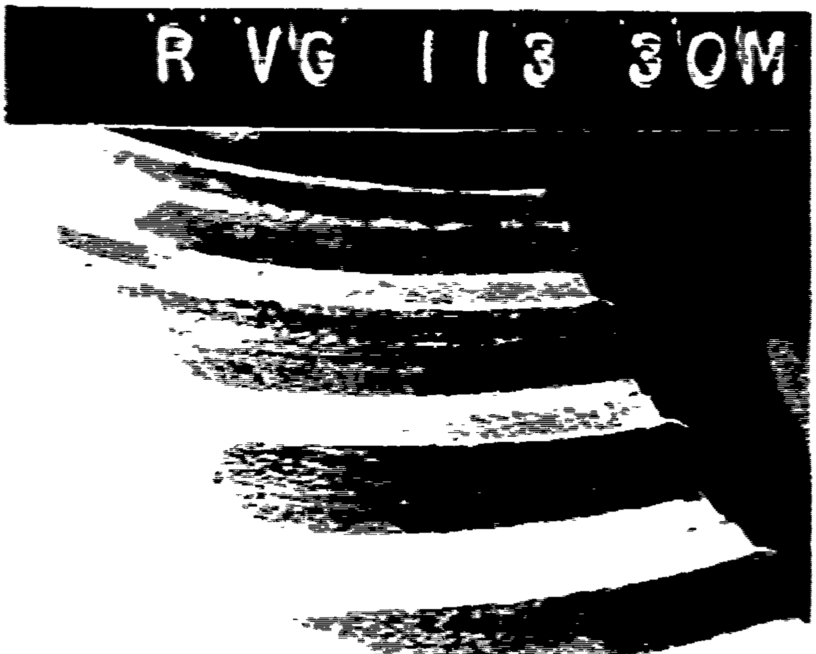
VASCO-X2 GEAR SET 5

Pinion Number A110

Gear Number A110

VASCO-X2 GEAR SET 6

Pinion Number A112



Gear Number A113

The evidence of metal flow on the pinion gear teeth is a good indication that the temperature experienced by the pinion blank was in excess of 1000°F. The temperature gages were missing from the pinion and found in the test housing. All of the temperature dots on the sensor plates had turned black.

In view of the extensive damage sustained during this test run, it may be said that this test could have been curtailed earlier. However, since there was no previous experience with testing conducted in this environment, it was mandatory to continue the test run long enough to sustain a reasonable degree of damage.

Baseline Gear Set Number 2 - Inspection of the temperature gages after run-in testing revealed that the low-temperature (230°F, 240°F, 250°F, 260°F) dots were exposed. In addition, one high-temperature (350°F) dot was exposed, but this was believed to be the result of a breakdown in the protective coating. Visual inspection of the tooth surfaces at the end of nonlubrication testing revealed severe scoring and metal flow, heat discoloration, and destructive pitting on the drive side of the pinion member. Heavy scoring was evident on the driven side of the mating gear member, along with a lesser degree of pitting. Contact patterns were visible on the coast side of both members, indicating contact on both sides of the teeth, which would present evidence that the installation backlash was taken up in thermal expansion. Pinion blank temperature checks were made within minutes of shutdown. These checks indicated that the pinion-blank temperature was between 788°F and 840°F. This would indicate a softening of the carburized case, since AISI 9310 steel has a tempering temperature of approximately 350°F.

Baseline Gear Set Number 3 - Visual inspection of the tooth surfaces at the end of nonlubrication testing revealed heavy scoring in the addendum and dedendum of the pinion member, with pitting at the pitchline. Scoring and pitchline pitting were evident on the mating gear member, but to a considerably lesser degree. Contact patterns were visible on the coast side of both members; however, they were much lighter and covered less area than the patterns resulting from the 100-percent load level testing.

Baseline Gear Set Number 4 - Visual inspection of the tooth surfaces of both members at the end of nonlubrication testing revealed conditions very similar to the third baseline test set.

Baseline Gear Set Number 5 - Visual inspection of the tooth surfaces at the end of nonlubrication testing revealed moderate to heavy scoring, and moderate pitting at the pitchline of the pinion member. The same condition prevailed on the tooth surfaces of the gear member, but with less severity. The pinion blank temperature checks indicated a blank temperature between 250°F and 300°F, and the 230°F temperature dot was exposed as well.

Baseline Gear Set Number 6 - Visual inspection of the tooth surfaces of both members at the end of nonlubrication testing revealed conditions very similar to the fifth baseline test set.

VASCO-X2 Gear Set Number 1 - After the first 50-percent load run-in, inspection of the temperature plate gages indicated that all of the lower temperature and three of the higher temperature dots were exposed. This exposure was believed to be the result of failure of the protective coating and exposure to the lubricating oil.

Visual inspection of the gear tooth surfaces at the end of nonlubrication testing revealed heavy scoring and pitting on the driven side of the pinion member. Scoring and pitting were evident on the driven side of the mating gear member; however, the damage was not as severe when compared to the pinion member. There was no visible evidence of cracks on either member. Contact patterns were visible on the coast side of both members, indicating that the installation backlash was insufficient to counteract thermal expansion during the nonlubrication testing.

VASCO-X2 Gear Set Number 2 - Visual inspection of the gear tooth surfaces at the end of nonlubrication testing revealed severe scoring and heavy pitting at the pitchline of the pinion member. In addition, metal debris was deposited on the coast side, particularly near the heel end. The gear member displayed scoring and pitting similar to the pinion, but with less severity. There was no visible evidence of cracks on either member. Contact patterns were visible on the coast side of both members, indicating that the installation backlash was insufficient to counteract thermal expansion during the nonlubrication testing.

VASCO-X2 Gear Set Number 3 - Visual inspection of the gear tooth surfaces at the end of nonlubrication testing revealed severe

scoring and heavy pitting at the pitchline of the pinion member. In addition, metal debris was deposited along the tooth surfaces. The gear member displayed scoring and pitting similar to the pinion, but with less severity; the tooth surface of the gear member and the topland were rough with metal that had been deposited in these areas. There was no visible evidence of cracks on either member. Contact patterns were visible on the coast side of both members, indicating that the installation backlash was insufficient to counteract thermal expansion during the nonlubrication testing.

VASCO-X2 Gear Set Number 4 - Visual inspection of the gear tooth surfaces at the end of nonlubrication testing revealed heavy scoring and moderate pitchline pitting of the pinion member. The gear member displayed scoring and pitting similar to the pinion, but with less severity. Contact patterns were visible on the coast side of both members, however they were much lighter and covered less area than any of the previous tests. There was no visible evidence of cracks on either member.

VASCO-X2 Gear Set Number 5 - Visual inspection of the gear tooth surfaces at the end of nonlubrication testing revealed moderate scoring and pitchline pitting of the pinion member. The gear member displayed similar conditions, but with less severity. There was no visible evidence of cracks on either member.

VASCO-X2 Gear Set Number 6 - Visual inspection of the gear tooth surfaces at the end of nonlubrication testing revealed heavy scoring and moderate pitchline pitting of the pinion member. The gear member displayed similar conditions, but with less severity. There was no visible evidence of cracks on either member.

METALLURGICAL EVALUATION

A destructive metallurgical examination was performed on one baseline spiral bevel pinion (serial number A103) subjected to the 100-percent load level and run for 13.5 minutes, and on one VASCO-X2 steel spiral bevel pinion (serial number A101) subjected to the 100-percent load level and run for 23 minutes. The results of this investigation are shown in Figures 18 and 19.

Both test pinions displayed excessive wear on the drive side of the tooth profiles, resulting in a wearing away of most of the carburized layer. Plastic flow of metal from the drive

flank over the tip onto the coast side was apparent on both test pinions.

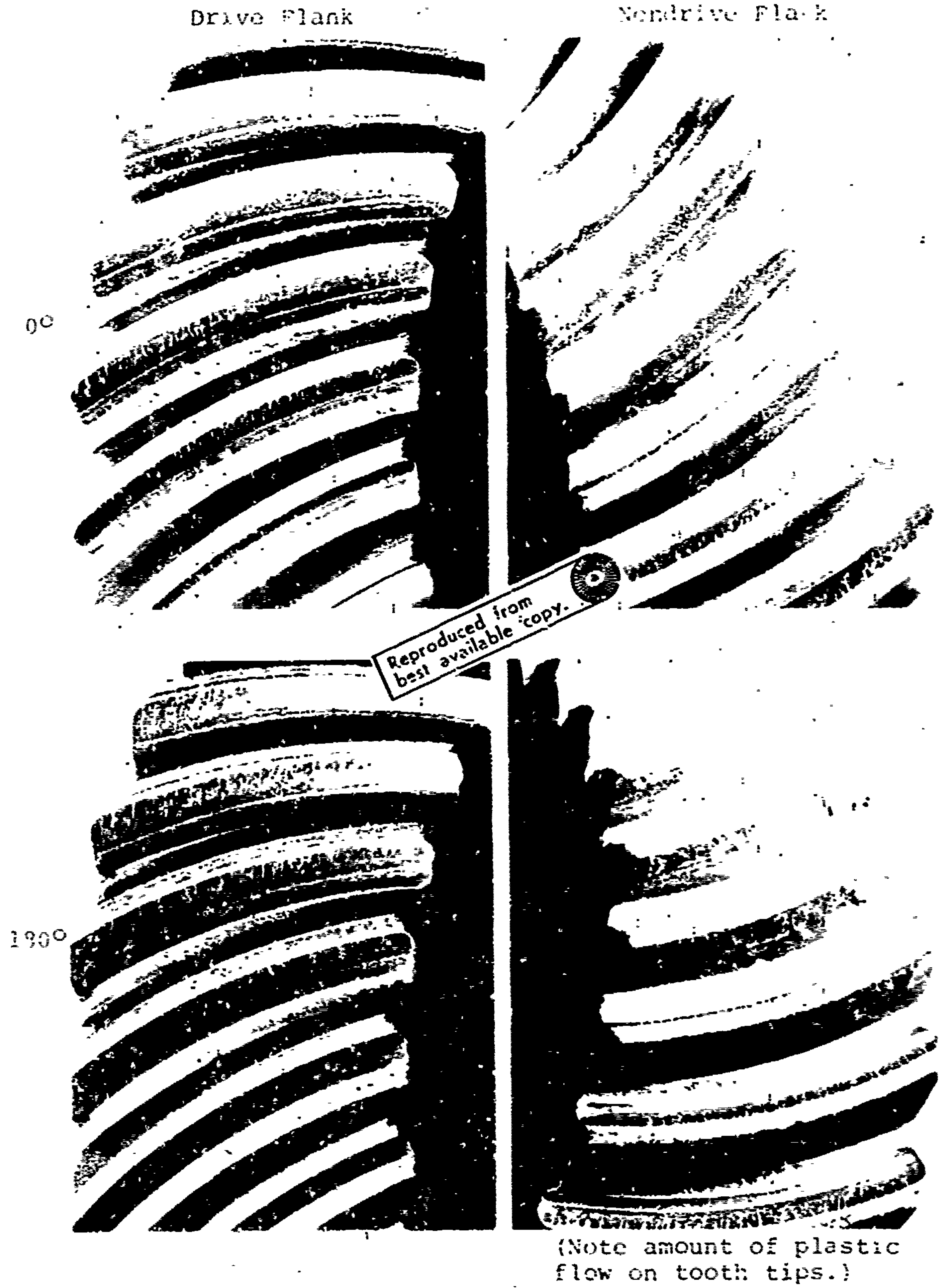
In general, the metallurgical examination revealed that both test pinions were subjected to extremely high temperatures. The VASCO-X2 pinion displayed streaks of radial rehardening, shown in Figures 20 and 21, on the drive flank of each tooth. A section taken through one of these localized streaks is shown in Figure 21. It is estimated that this area was subjected to a temperature in excess of 1700°F.

Table XII presents a comparison of hardness along the tooth profile of the two test pinions at the toe and heel positions at two locations 180° apart. This table reveals a higher hardness for the VASCO-X2 pinion along the entire tooth profile and in the tooth core. Figures 22 and 23 present metallographic profiles of the gear teeth. Figure 24 shows effective case depth of selected positions.

Drive Flank   Nondrive Flank

(Note amount of plastic flow on tooth tips)

Figure 18. Baseline Pinion Gear (A103) After 13.5 Minutes of Oil Starvation at 100-Percent Load.



(Note amount of plastic flow on tooth tips.)

Figure 19. VASCO-X2 Pinion Gear (A101) After 23 Minutes of Oil Starvation at 100-Percent Load.

Baseline
(No rehardening characteristics exhibited)

VASCO-X2
(Rehardening characteristics exhibited on each tooth addendum)

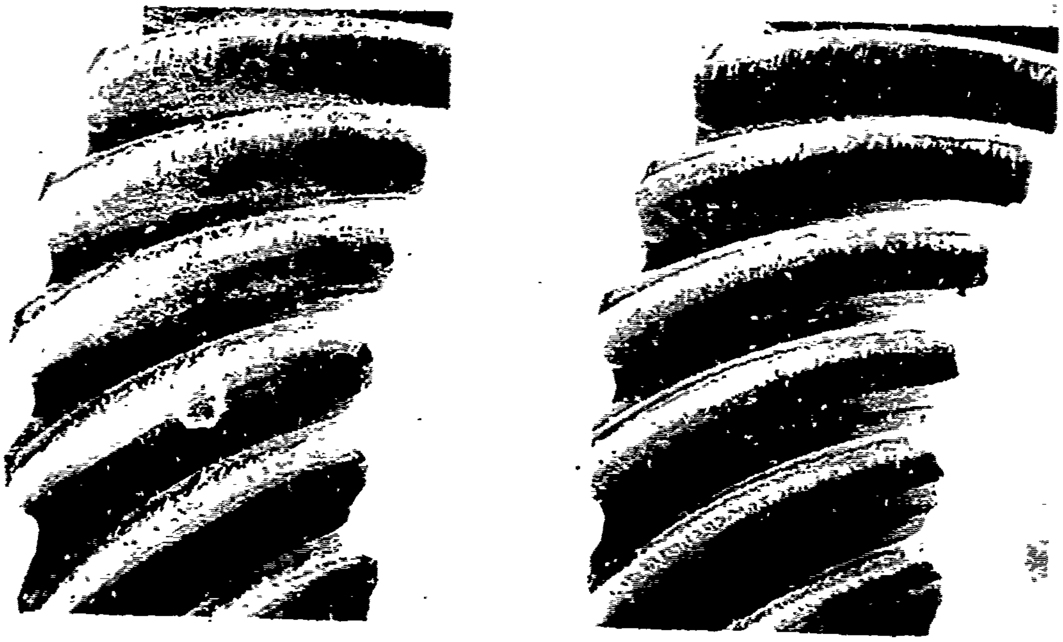


Figure 20. Baseline and VASCO-X2 Pinion Gears (A103 and A101) After Nital-Etch Inspection.

Radial Rehardening Streaks (11X)

Metallographic Section Through Rehardening Area; Maximum Depth, .001 Inch. (500X)

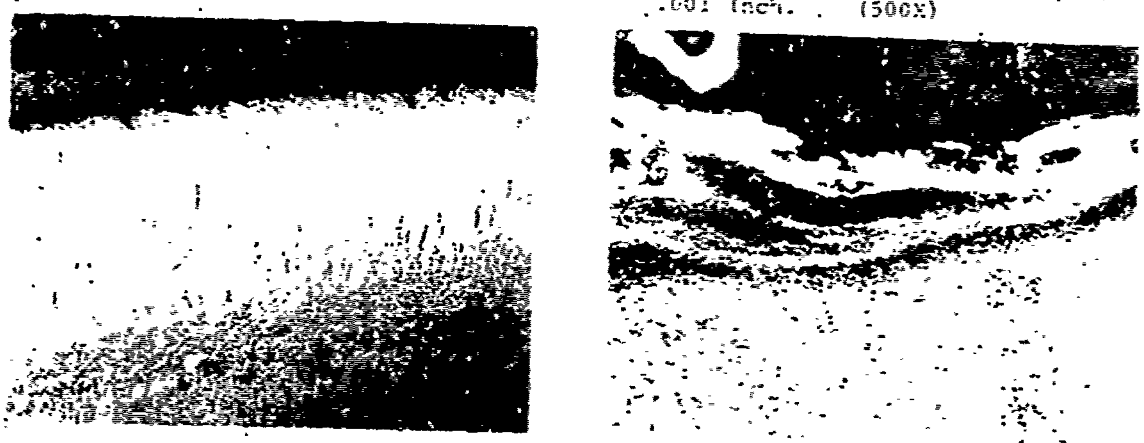


Figure 21. Rehardening Characteristics Exhibited by VASCO-X2 Pinion Gear (A101) After Nital-Etch Inspection.

TABLE XII. HARDNESS DETERMINATION			
		Rockwell "C" Hardness	
Location on Teeth		Baseline Pinion (A103)	VASCO-X2 Pinion (A101)
0° Diameter			
Adjacent to surface in carburized area			
Drive flank	- toe position	39	55
	heel position	37	52
Nondrive flank	- toe position	47	58
	heel position	44	54
Root	- toe position	44	55
	heel position	40	54
Core of tooth (approximately 0.1 inch from surface)	- toe position	30-32	46
	heel position	27-28	45-46
180° Diameter			
Adjacent to surface in carburized area			
Drive flank	- toe position	42	40
	heel position	39	38
Nondrive flank	- toe position	49	54
	heel position	45	43
Root	- toe position	48	52
	heel position	44	46
Core of tooth (approximately 0.1 inch from surface)	- toe position	33-36	45
	heel position	30-31	35-38

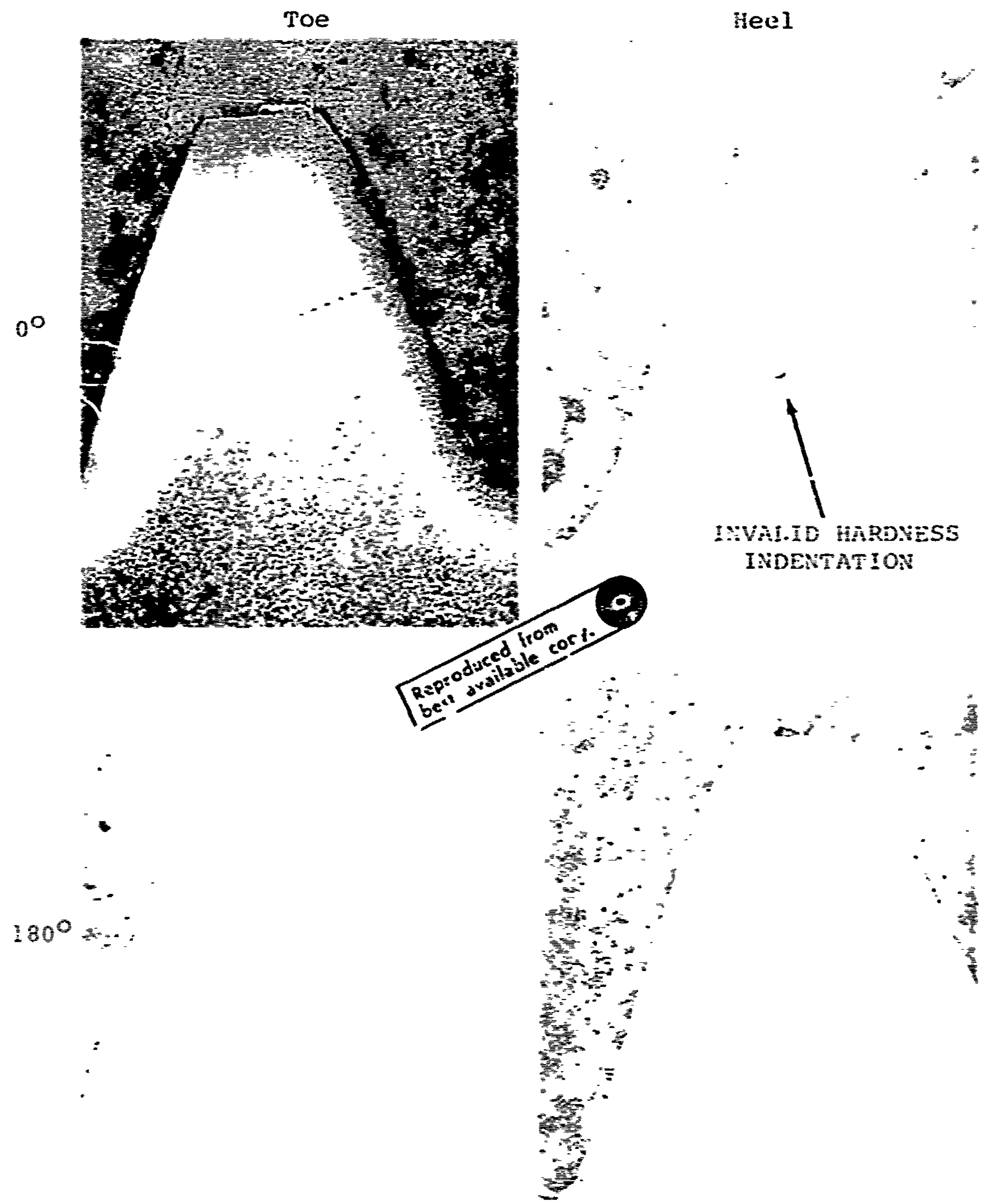


Figure 22. Metallographic Profile of Tooth From Baseline Pinion Gear (A103), Exhibiting Wear and Deformation of Drive Flank Carburized Case (9X).

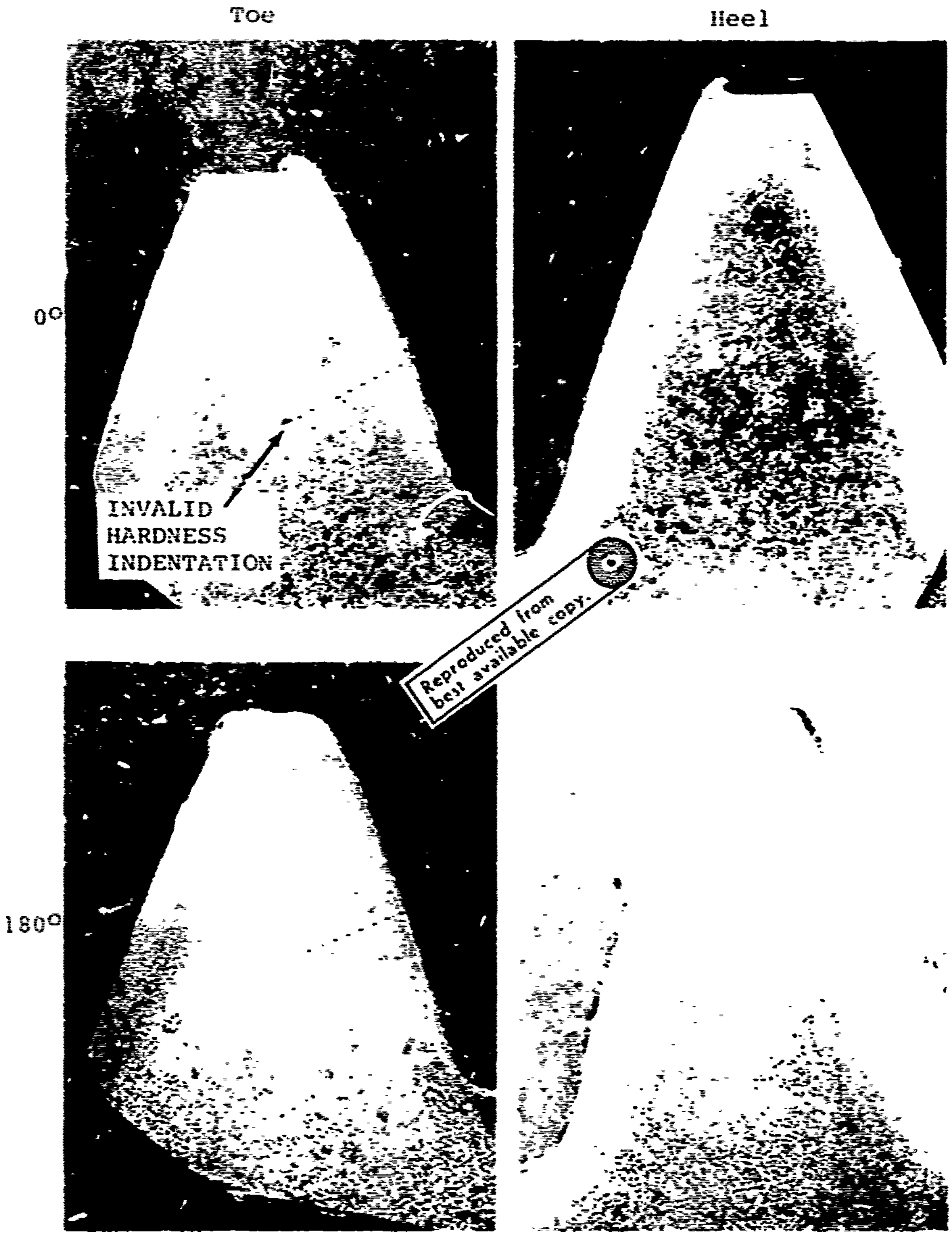


Figure 23. Metallographic Profile of Tooth From VASCO-X2 Pinion Gear (A101), Exhibiting Wear and Deformation of Drive Flank Carburized Case (9X).

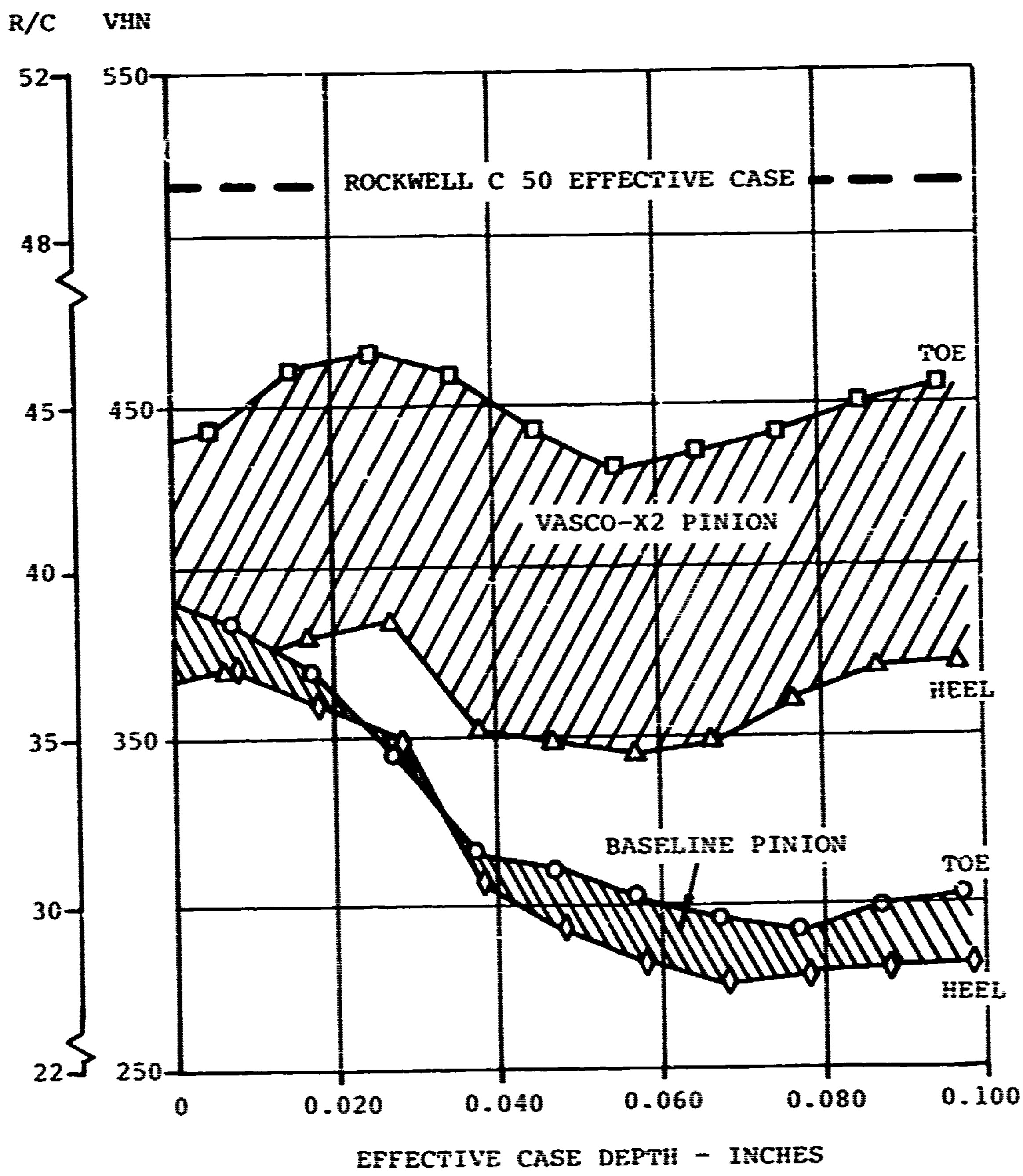


Figure 24. Effective Case Depths and Hardness Traverse Data of Drive Flanks at the 180° Position.

CONCLUSIONS

1. The proposed method of measuring blank temperature by the use of gages during the nonlubrication testing proved to be unsuccessful due to exposure of the gages to the lubricating oil and/or exposure to the excessively high temperatures. A substitute method employing thermal crayons was utilized as a backup. This method can only be used at the conclusion of the individual tests, and it is a judgement evaluation with regard to color change in a specified time interval. Therefore, the accuracy of this method is questionable as to the determination of the actual gear-blank temperature. However, these temperature determinations were used as index numbers for comparisons between tests.

2. Destructive metallurgical evaluation of both a 9310 steel pinion and a VASCO-X2 steel pinion (after completion of the 100-percent load nonlubrication test) revealed considerable metal flow in both cases. This would conservatively indicate pinion-blank temperatures exceeding 1100°F. It is therefore concluded that gears fabricated from different compositions of steel, subjected to these temperature levels, will not provide significant improvements in nonlubricated operating time.

3. This test program utilized spiral bevel gears which were reground to restore the tooth surfaces. The regrind increased the installation backlash by approximately twice the design backlash. Results of the nonlubrication testing at the 85-percent and 100-percent load levels indicated that contact was made on both sides of the teeth. This was evidenced by the resulting coast patterns on both members (pinion and gear). This indicates that even with the increased backlash, there was insufficient clearance to accommodate thermal expansion during the nonlubrication testing. It can be concluded that standard backlash could have resulted in an early failure.

4. Both the VASCO-X2 steel spiral bevel gears and the AISI 9310 steel spiral bevel gears successfully completed nonlubrication testing for 30 minutes at the 75-percent load level. Visual examination of the gear tooth surfaces indicated light surface distress in both cases. This would indicate that the operating load level has a significant effect on gear performance in a nonlubricated environment. However, it should be noted that this test was conducted with increased backlash and in the moderate speed regime (pitchline velocity, 5360 feet per minute). Comparisons should be restricted to designs with comparable parameters.

5. Experimental gear testing usually results in significant data scatter, thereby requiring a sufficient number of test specimens to accomplish a statistical evaluation of the test results. This program consisted of a very small number of test specimens; consequently, the test results generated by this program should be evaluated with discretion.

RECOMMENDATIONS

Based on the results obtained from the experimental testing and from the evaluation performed in the execution of this program, it is recommended that further work be directed in the following areas:

1. Conduct a destructive metallurgical examination of the VASCO-X2 steel spiral bevel gears and the AISI 9310 steel spiral bevel gears which survived the 75-percent load testing (nonlubrication), to establish a comparison of the effect of the reduced load on the two gear materials.

2. Conduct an experimental test program with AISI 9310 (AMS6265) and VASCO-X2 steel spiral bevel gears operating under conditions of minimum oil flow to sustain continued operation for at least 30 minutes. This proposed program would provide essential data for the design of emergency helicopter transmission lubrication systems, incorporating concepts such as the viscous pump.

SELECTED BIBLIOGRAPHY

1. Martin, H. M., THE LUBRICATION OF GEAR TEETH, Engineering, Volume 102, 1916.

2. Blok, H., MEASUREMENT OF TEMPERATURE FLASHES ON GEAR TEETH UNDER EXTREME PRESSURE CONDITIONS, Proc. Gen. Disc. on Lubrication, 1937.

3. Blok, H., THEORETICAL STUDY OF TEMPERATURE RISE AT SURFACES OF ACTUAL CONTACT UNDER OILINESS LUBRICATING CONDITIONS, Proc. Gen. Disc. on Lubrication, 1937.

4. Institute of Petroleum Gear Lubrication Symposium, London, England, February 1952, Journal Institute of Petroleum, 1952.

5. ASLE Gear Lubrication Symposium, Chicago, Illinois, January 1959, Lubrication Eng. and ASLE Trans., 1959.

6. Institute of Petroleum Gear Lubrication Symposium, Brighton, England, October 1964.

7. Almen, J. O., DIMENSIONAL VALUE OF LUBRICANTS IN GEAR DESIGN, SAE Journal, Volume 50, Number 9, Page 373, 1942.

8. Kelley, B. W., and Lemanski, A. J., LUBRICATION OF INVOLUTE GEARING, Proc. I. Mech. E., Volume 182, Pt. 3A, Pages 173-184, 1967-1968.

9. Blok, H., SURFACE TEMPERATURES UNDER EXTREME PRESSURE CONDITIONS, Second World Petroleum Congress, Paris Section 4, 1937.

10. Ibrahim, M., and Cameron, A., OIL FILM THICKNESS AND THE MECHANISM OF SCUFFING IN GEAR TEETH, Lubrication and Wear Convention, 1963, Institute of Mechanical Engineers, London.

11. Askwith, T. C., Crouch, R. R., and Cameron, A., THE RELATIONSHIP OF LUBRICANTS AND ADDITIVES FOR OPTIMUM EFFECT AND A THEORY OF SCUFFING, Proc. Symposium on Gear Lubrication, Institute of Petroleum, 1966.

12. Coleman, W., A SCORING FORMULA FOR BEVEL AND HYPOID GEAR TEETH, Journal of Lubrication Technology, ASME, Volume 89F, Page 114, 1967.

13. Grubin, A. N., and Vinognadova, I. E., INVESTIGATION OF THE CONTACT OF MACHINE COMPONENTS, Book Number 30, Moscow 1949, DSIR, London, Translation Number 337.

14. Chen, H. S., CALCULATION OF ELASTOHYDRODYNAMIC FILM THICKNESS IN HIGH SPEED ROLLING AND SLIDING CONTACT, MTI Report Number 67TR24.

15. Benedict, G. H., and Kelley, B. W., INSTANTANEOUS COEFFICIENTS OF GEAR TOOTH FRICTION, ASLE Transactions, Volume 4, Number 1, April 1961.

16. Leach, E. F., and Kelley, B. W., TEMPERATURE - THE KEY OF LUBRICANT CAPACITY, ASLE Paper 64LC-13, 1964.

17. Blok, H., LUBRICATION AS A GEAR DESIGN FACTOR, Proceedings of the International Conference on Gearing, Institute of Mechanical Engineers, 1958.

18. Kelley, B. W., A NEW LOOK AT THE SCORING PHENOMENA OF GEARS, SAE Transactions, Volume 61, 1953.

19. Lemanski, A. J., GEAR SCORING DESIGN GUIDE FOR AEROSPACE SPUR AND HELICAL POWER GEARS, American Gear Manufacturers Association Information Sheet 217.01, October 1965.

20. Dudley, D. W., PRACTICAL GEAR DESIGN, McGraw Hill Book Company, Inc., New York, 1954.

21. Bodensieck, E. J., SPECIFIC FILM THICKNESS - AN INDEX OF GEAR TOOTH SURFACE DETERIORATION, AGMA Technical Division Meeting, 1965.